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A Team Distribution Model of Post-Disaster Search and Rescue Considering Information Accuracy Difference

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Post-disaster search and rescue is an information-depending systematic process. Accurate information helps to provide decision support for SAR by optimizing SAR teams' distribution. During the SAR process, information source is one of the main factors influence information accuracy. Among various sources, positioning device is one of the primary information sources. The purpose of this paper is to investigate whether different sources lead to different information accuracy and whether the accuracy difference influences SAR efforts. A network model is presented to describe the distribution of SAR teams and a simple algorithm is developed to solve the model. Then a numerical example is performed to test the model and algorithm.

1. Introduction

Timely and effective post-disaster search and rescue (SAR) determines the total quantity of fatalities in most cases. As an important part of emergency management research, SAR researches are based on experience summary of SAR practice or statistical data (McIntosh et al., 2010; Hung and Townes, 2007). Nowadays the researches about SAR are mainly focusing on the emergency logistics (Fiedrich et al., 2007; Yuan and Wang, 2009; Nagy and Salhi, 2007; Sheu, 2007) and emergency decision-making (Janis and Mann, 1977; Kapucu and Garayev, 2011). Because of destructive communication and incomplete emergency system comprehensive and accurate information cannot be got timely. So for the front-line SAR teams, the search operations for survivors may carry out randomly. However with the development of rescue efforts, kinds of effective information obtained from various channels constantly. High accuracy information is likely to change the search strategies or methods. Therefore, abstract the SAR operations as a series of simple systematic search or random search process is unable to effectively describe the actual rescue procedure. In this paper, we will explore how information with different accuracy improves SAR efficiency by influencing the search time and rescue pattern.

Disaster emergency is a typical information-depending decision-making process. The rapid development of information technology provides a variety of information acquisition means, such as GPS, mobile communication technology, vibration detection and so on. Take full advantage of these equipment helps to provide dynamic and timely information for SAR. In addition, there are two kinds of important but easy to ignore information sources: the handheld positioning device of front-line SAR teams and the survivors that have been rescued. The first-hand information about the disaster area will be shared among all SAR teams so as to reduce blindness and randomness of SAR work. Thus it can be observed that information source may influence the accuracy of information and then affect the SAR efficiency. It will be discussed in this paper.

2. Basic assumption

2.1 The Problem

Consider the following scene: A remote region was attacked by flood and most of the region were ruined. The region was divided into several grids and quantity of survivors were waiting for rescue. After disaster only a few paths were still passable and their conditions can be observed. Due to the damage of the communication network, the rescue center could only get the approximate location of survivors through mobile phone signals. SAR teams can learn each other's position and path selection information, however they had to cruise to search and find more survivors. Suppose the rest available paths in this region as a passable grid net G (V, A), in which V is the set of nodes and A is the set of arcs (linked roads) in the network. There are a quantity of SAR teams searching survivors in the road network, and the quantity is constant for simplicity. We suppose all survivors will be sent to rescue center within the time period *T*, then $t \in T$.

For simplicity the grid net *G* is divided into several grids, let *g* be one of them ($g \in G$). Assuming that there are still some survivors in grid g at time *t*, let it be $S_g(t)$. Then $S_g(1)$ is equal to the number of survivors in grid *g* at the initial time. Let *S* be the total number of survivors in the network, then

$$S = \sum_{g \in G} S_g(1) \tag{1}$$

Eq(1) shows that the total number of the survivors is the sum of survivors in each gird at the initial time. Assume that the remaining passable paths are not congested, and there is no delay because of queue or danger.

Let t_{gm} be the travel time from *m* to grid *g*, and t_{mg} is constant.

2.2 The Behavior of SAR

Via satellite maps and GPS system, the SAR teams can learn from the situation of paths in the disaster area more accurately. Meanwhile, through some mobile applications the rescue center could obtain the distribution of SAR teams more conveniently. Therefore, for the SAR teams, the accuracy of their own location information is better than the accuracy of the survivors' positioning information they get. Suppose there are a lot of SAR teams (N) searching for survivors independently in the network. All SAR teams will origin from rescue center m to each grid at the initial time. Let $N_{\mathrm{m}}(t)$ be the number of SAR teams at medical center m at time t, so

$$N = N_m(1) \tag{2}$$

As shown in Eq(2), all SAR teams gatherer at rescue center m at the initial time (t=1). Let $N_{\mathrm{g}}(t)$ be the number of SAR teams searching in grid g at time t.

The SAR teams are not clear about the exact location of survivors, so they have to cruise independently to search for survivors. Due to the terrible conditions and poor information management in disaster scene, we do not consider the unitive rescue operation system here. The SAR teams will carry out independent and scattered search. When the SAR teams find survivors, some basic treatment should be done and then the survivors will be sent to the rescue center. After that the teams can begin a new round of SAR operation.

Consider one SAR team reaches grid g at time t and it spends time $c_g^s(t)$ in finding a survivor. Let c_g^r be the rescue time (where the letter s, r means search and rescue respectively). c_g^r is assumed to be constant for simplicity. So the search cost of each round SAR is the sum of travel time, search time and rescue time,

$$C_{mg}(t) = c_{mg} + c_g^s(t + c_{mg}) + c_g^r \tag{3}$$

Where $C_{mg}(t)$ is the search cost of the team from the rescue center m to grid g at time t, note that the SAR team reaches grid g at time $t + c_{mg}$.

All SAR team have to search survivors as soon as possible so as to increase the efficiency, which means they should minimize the search cost of each round. Nevertheless, $c_g^s(t)$ will change with the variation of disaster conditions, so the SAR teams should make full use of information to determine target grids. Although the SAR teams all origin from node m, their target grids are different. Search time usually is determined by several factors, such as the positioning accuracy, the type and severity of disaster, the size of grid g, the number of SAR teams, and the quantity of survivors and so on.

After SAR teams send the survivors to the rescue center, this round of SAR task ends and a new round begins. They can either continue to search in the same grid, or move to another grid to search for new survivors. We suppose each SAR team tries to minimize search time and optimize the target grid with instantaneous position information.

2.3. Expected Search Time for Survivors

In this section, we will derive the expected search time $c_g^s(t)$ in grid g at time t based on the discussion above.

Suppose that the SAR teams only estimate search time according to current information, and there are $S_g(t)$ survivors and $N_{\mathrm{g}}(t)$ SAR teams in grid g at this moment. Suppose the survivors in the grid network are uniformly distributed. Although the exact location is not certain, we can obtain the distribution density. Let the total road length be A_g, and the distribution density be ρ_g,

$$\rho_g = S_{\mathrm{g}}(1)/A_g \tag{4}$$

Where $\rho_g$shows the distribution density of survivors in grid g. Suppose a team's search speed is v. After per unit time the search distance is $v \cdot \Delta t$, and the probability of finding a survivor is$\rho_g v\Delta t$, so

$$\alpha_g = \rho_g v\Delta t \tag{5}$$

Where α_g is the search parameter, which shows the search difficulty in this grid. The less α_g means sparser survivors distribution and higher search difficulty. At time t, there are $N_g(t)$ SAR teams, and after a unit time the number of survivors has been found is $\alpha_g N_g(t)$. And those survivors that meet SAR teams will be sent to the rescue center,

$$f_{gm}(t) = \alpha_g N_g(t) \tag{6}$$

$f_{gm}(t)$ is the number of SAR teams back to rescue center m from grid g. Note that, the quantity of SAR teams searching in grid reduces by $f_{gm}(t)$ at the same time,

$$N_g(t+1) = N_g(t) - f_{gm}(t) = N_g(t)(1-\alpha_g) \tag{7}$$

Similarly, at time (t+x),

$$N_g(t+x) = N_g(t)(1-\alpha_g)^x \tag{8}$$

Now $N_g(t+1) \sim N_g(t+x)$ form a geometric sequence. When $N_g(t+x^*)$ equals 1, the value of x^* closes to the time that all survivors have been found. Based on the sequence,

$$x^* = lnN_g(t)/ln(1-\alpha_g)^{-1} \tag{9}$$

Then we can get the expected search time$(x^*/2)$, for a SAR team reaches grid g and search in this grid at time t. α_g can be obtained by the survey parameters, so

$$c_g^s(t) = lnN_g(t)/2\ln(1-\alpha_g)^{-1} \tag{10}$$

3.The Team Distribution with Information Available

3.1. The Rescue Behavior and the Instantaneous Information

All SAR teams leave for target grids from rescue center m at initial time. The total quantity of survivors is known, but their exact location is not clear. So the SAR teams can only leave for each grid to search by cruising. According to the signals from electronic device, the SAR teams still can get some allocation information about survivors. It's assumed that the SAR teams can get some continues and instantaneous information and they can get the distribution of SAR teams and the quantity of rescued survivors. Take this into account, the SAR teams can assess the search difficulty of each grid and choose target grids. The SAR teams have to cruise in target grids for survivors because they don't know the exact position of survivors.

In order to improve efficiency, each SAR team need to find as many survivors as possible, and minimize the rescue cost. Note that there are $N_m(t)$ teams at rescue center m at time t. Let the rescue cost leaving for grid g be $C_{mg}(t)$, and there is a positive correlation between rescue cost and the number of SAR teams, which means it will reduce the SAR efficiency if there are too much SAR teams in one grid. Therefore in an ideal state the rescue cost of each team should be equal at time t,

$$C_{mg}(t) = C_{mg'}(t), \forall g \neq g' \tag{11}$$

Now the problem transforms into a typical network distribution problem. During the distribution process SAR teams need to select the target grid first according to the instantaneous team allocation information, and then they cruise for searching for survivors after arriving at the target grid.

3.2. The Distribution Model

When SAR teams with survivors go back to the rescue center m, this round of rescue task finishes and a new rescue task begins. At time t, the total of SAR teams from m is $N_m(t)$. Let the number of teams from the rescue center to each grid to be $f_{mg}(t)$, and similarly, we can get the number of teams back to rescue center from each grid. As the number of SAR teams at the initial time is known, so

$$N_g(t) = N_g(t-1) - f_{gm}(t) + f_{mg}(t - c_{mg}) \tag{12}$$

As shown in Eq(12) above, the original number of SAR teams in grid g is $N_g(t-1)$ at time t, then $f_{gm}(t)$ teams find survivors and go back to the rescue center, at the same time $f_{mg}(t-c_{mg})$ teams reach grid g and begin to search. Note that SAR teams spend time c_{mg} to reach grid g, so they begin to search at time$(t-c_{mg})$. The quantity of SAR teams at the rescue center at time t is

$$N_m(t) = N_m(t-1) - \sum_{g\in G} f_{mg}(t) + \sum_{g\in G} f_{gm}(t-c_{mg}) \tag{13}$$

Eq(13) shows that subtracting the teams leaving for each grid ($\sum_{g\in G} f_{mg}(t)$) from the former number of teams at the rescue center, and adding the teams back from each grid ($\sum_{g\in G} f_{gm}(t-c_{mg})$), we can get the quantity of SAR teams at the rescue center at time t. At that time the number of survivors is

$$S_g(t) = S_g(t-1) - f_{gm}(t-1) \tag{14}$$

Based on the former discussion, the SAR teams origin from m should satisfy the following conditions: let $C_m^*(t)$ to be the minimum search cost $C_m^*(t) = \min\{C_{mg}(t), \forall g \in G\}$, and
for $f_{mg}(t)$

$$C_{mg}(t) \le C_m^*(t),\ f_{mg}(t) \ge 0 \tag{15}$$

Otherwise if $C_{mg}(t) > C_m^*(t)$, which means SAR teams are too dense in grid g and the rescue cost is too high, the teams should select other grids. According to Eq(15) we can get the SAR teams' distribution from rescue center m to each grid. The number of SAR teams back to rescue center from each grid can obtain based on the analysis in section 3.

4. A Solution Algorithm

As mentioned above, the nonlinear equations above can be solved by network distribution method. But it needs to be noted that this problem consists of two loops, where one loop is used to calculate the search time in one grid, and the other loop is used to calculate the distribution flow. The basic idea is on the basis of initial value, iterate step by step for optimal solution. Details are as follows:

Step 1. Initialization. Let all variables $\{N_m(t),\ N_g(t),\ f_{mg}(t), f_{gm}(t)\}$ be the initial value according to the constraints and conditions. Set iteration counter k=0.

Step 2. Update. Set k=k+1. Compute $N_g(t)^{(k)}, \forall g$, according to,

$$N_g(t)^{(k)} = N_g(t-1)^{(k-1)} - f_{gm}(t-1)^{(k-1)} + f_{mg}(t-c_{mg})^{(k-1)}$$
$$S_g(t)^{(k)} = S_g(t-1)^{(k-1)} - f_{gm}(t-1)^{(k-1)}$$

Step 3. Compute Search time, according to,

$$c_g^s(t)^{(k)} = \ln N_g(t)^{(k)} / 2\ln(1-\alpha_g)^{-1}$$

Step 4. Compute search cost $C_{mg}(t)^{(k)}, \forall g$, according to the following equation, and compute $C_m^*(t)^{(k)}$.

$$C_{mg}(t)^{(k)} = c_{mg} + c_g^s(t+c_{mg})^{(k)} + c_g^r$$

Step 5. Assign the search teams, this yields $f_{mg}(t)^{(k)}$.

Step 5.1. if $C_{mg}(t)^{(k)} > C_m^*(t)^{(k)}$,

$$f_{mg}(t)^{(k)} = f_{mg}(t)^{(k-1)} \cdot [1-(1/k)\left(1-C_{mg}(t)^{(k)}/C_m^*(t)^{(k)}\right)].$$

Step 5.2. if $C_{mg}(t)^{(k)} \le C_m^*(t)^{(k)}$,

$$f_{mg}(t)^{(k)} = f_{mg}(t)^{(k-1)} \cdot [1+(1/k)\left(1-C_{mg}(t)^{(k)}/C_m^*(t)^{(k)}\right).$$

Step 6. Convergence test. If all search teams arrive at their destinations, which means $|f_{mg}{}^{(k)} - f_{mg}{}^{(k-1)}| < \epsilon$, where ϵ is a predetermined convergence tolerance, stop; otherwise, go to step 2.

5. A Numerical Example

Consider an example as showed in Figure. 2 with a rescue center m and four grids 1, 2, 3, 4. The region is attacked by a flood disaster and needs to be rescued now. It is illustrated in Figure. 2 In each grid, there are S_g survivors waiting for SAR, and the number S_g can be obtained through the mobile phone signals of survivors，where $S_1 = 30, S_2 = 40, S_3 = 60, S_4 = 30$. Each grid is connected by a direct path and every path is bidirectional.

Suppose that five minutes to be one time unit and the travel time between each grid is presented in Table1.

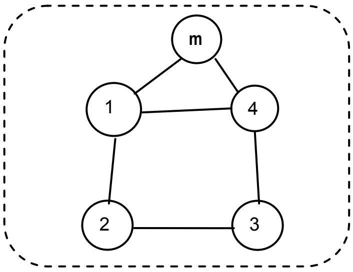

Figure1. The Grid Network

Table 1. Link travel time (time unit period)

Link	1-2	2-1	2-3	3-2	3-4	4-3	1-4	4-1	1-m	m-1	4-m	m-4
Time	2	2	3	3	4	4	4	4	4	4	2	2

The search and rescue activities of SAR teams are divided into two parts: (1) choose the shortest path through the vehicle navigation and satellite maps and then go to the target grid; (2) after arrived at the target grid, search the whole grid by cruising. The time of basic treatment c_g^r is one time unit.

At the initial time t = 1, there are N (N =100) SAR teams waiting to search for survivors. We suppose that the SAR teams at rescue center m can choose the target grid by themselves according to the latest distribution information, in addition all relief efforts are required to complete in a certain time. According to the assumptions above, the distribution of SAR teams at any time can be obtained, as well as the quantity change of SAR teams in each grid. At the initial time (t = 1), all the 100 teams leave for each grid from the rescue center. By calculation we can get the flow distribution with $f_{m1}(1) = 13$, $f_{m2}(1) = 13$, $f_{m3}(1) = 53$, $f_{m4}(1) = 21$, as shown in Figure2.

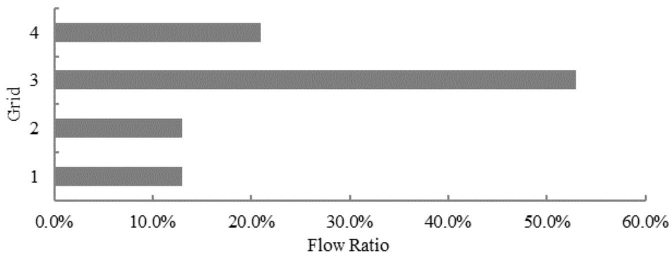

Figure 2. The Flow Ratio to Target Grids at Initial Time

At time unit 2, all teams are on the way to their target grids, so the number of SAR teams at the rescue center is 0. When SAR teams leave for target grids, they all choose the shortest paths, so the link flow at unit time 2 is depicted as shown in Figure3.

After 2 time units, several SAR teams arrived at grid 4 and found 3 survivors. After some rudimentary medical treatment the survivors were sent to the rescue center. The remaining 18 teams continued to search for survivors in grid 4. Similarly, after 4 time units 26 teams arrived at grid 1, then 13 teams stayed in grid 1 and searched for survivors and the rest of the teams went to grid 2. The SAR teams back to rescue center will leave for each grid again until all survivors are found. Suppose all survivors will be found in 30 time units. In addition, all SAR teams returned to the rescue center in 39 time units. As shown in Figure 4, fm1 represents the number of SAR teams from rescue center m to grid 1, and the rest can be taken in the same manner. Therefore, the model can describe how the information from different positioning device influences the SAR activities, and how the SAR teams improve their efforts with the help of these information.

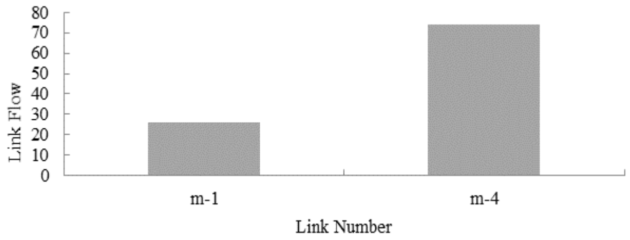

Figure 3. The Link Flow at Unit Time 2

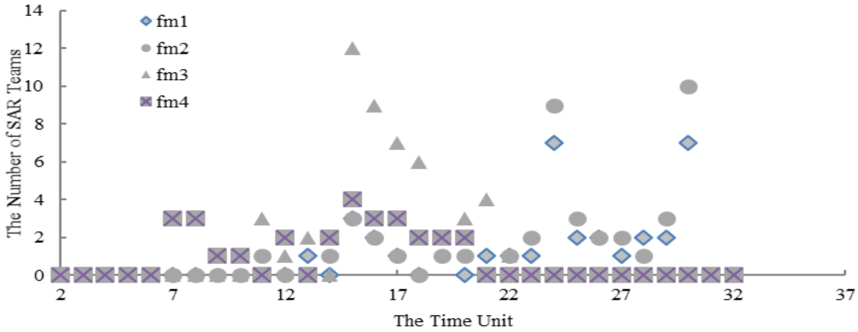

Figure 4. The SAR Team Distribution for Each Grid

6. Conclusions

Through the team distribution model, we find that information accuracy is a major factor that influences SAR operations. High accuracy information is likely to improve the SAR teams' distribution and then improve the SAR efficiency. The model offered some interesting insights into SAR team distribution research and offered some strategy-relevant results for decision making. Quite a lot of complex factors may influence the information accuracy of SAR, but we mainly discussed the information sources in this paper. So future researches will be undertaken to explore the other impact factors. Another limitation of this paper is that how to distinguish information accuracy has not been discussed. So the future research is committed to if information accuracy can be quantitative analyzed and how to improve the accuracy by data processing.

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