A Comparative Analysis on Dispatching of Post-Disaster Search and Rescue

Qianqian Liu¹, Qun Wang¹, Rongyi Du², Wenyong Li³

¹Business School, Hohai University, Nanjing 211106, China
²The Research Institute of Traffic Engineering and Science, Nanning Public Security Bureau, Nanning 530028, China
³School of Architecture and Traffic Engineering, Guilin University of Electronic Technology, Guilin 541004, China

Email: liuqq0312@foxmail.com

Abstract

The development of electronic information technology provides technique and equipment support for post-disaster search and rescue (SAR). It has also changed the operation pattern of SAR. Two basic types of SAR pattern are proposed here: central dispatch and independent search. The former pattern depends on a unified SAR management system, while the latter carries out independently according to instantaneous information. The research studies the corresponding conditions of SAR, models and algorithms. The idea of central dispatch is raised through dispatching rules, transforming independent search into a problem of network flow equilibrium. The validity of the model is verified by numerical examples. The results show that the central dispatch helps to distribute rescue forces to the most needed area, and the independent search based on real-time information indicates better effect, considering that the independent search takes both distributions of survivors and SAR teams into consideration. The results revealed in the numerical examples support the conclusion.

Keywords: search and rescue, SAR mode, central dispatch, independent search, information.

1. INTRODUCTION

Since the disasters are closely related with the security of human life and property, the scientific research into the post-disaster search and rescue is of great importance for practice. The development of technology enhances the capability of dealing with natural disasters and the understanding is deepened through scientific researches.

In order to save lives and reduce property losses caused by incidents, we not only need to perfect the early warning system and preventive measures, but also need to improve the
ability of search and rescue (SAR) in the post-disaster process. A quick and effective response after disaster helps to reduce the loss to the minimum extent. The basic objective of post-disaster search and rescue (SAR) is to “find, locate and rescue most survivors in shortest time". Namely, no matter in the maritime or land SAR, the process usually includes three basic steps: (i) SAR teams departing for the affected region from the rescue center; (ii) searching for survivors in the target region (in the following contents it will be described as a grid); (iii) finding survivors and sending them back to the rescue center.

Hitherto, a large number of researches have dived into post-disaster rescue and evacuation (Takeo, 1996; Lin et al., 2008; Alexander, 2009; Mohammad et al., 2009), rescue material dispatching (Haghani and Oh, 1996; Fiedrich et al., 2000; Sheu, 2007), vehicle path selection (Yuan and Wang, 2009; Batta et al., 2009; Zhang et al., 2013) and emergency decision-making (Janis and Mann, 1977; Danielsson and Ohlsson, 1999; Kapucu and Garayev, 2011), laying a solid theoretical foundation for the post-disaster rescue including the emergency system, improved emergency process and developed rescue equipment that have all posed positive effect on the post-disaster rescue practice. However, few researches have looked into the rescue path and influential factors by taking the after-rescue behaviors into account as a process of information sharing and cooperation, and without much attention being devoted to how dispatching pattern of SAR teams influences the SAR process. Besides, the simplification of the rescue process weakens the authenticity of the model.

The paper chose a new direction different from the past ones where the decision makers or leaders of the rescue are taken as the study subjects, no matter in the rescue material dispatching or vehicle path selection, and the view from the rescue teams is barely studied. But it is the rescue team, as the executor of the rescue that always stands on the front-line of the rescue and reach the survivors and the rescue site at first. Their rescue efficiency determines the efficiency of the whole rescue move. Faced with the complex post-disaster environment and emergencies, the rescue team may be unable to exactly follow the original rescue plan. The prearranged rescue plan, mode and method should be flexible enough considering the changing post-disaster environment. Therefore, except for optimizing the rescue decision-making from a macroscopic view, the discussion is also necessary over the rescue mode and behavior of the rescue team, which could help to improve the rescue efficiency of the team.

In order to allocate resources reasonably and improve the efficiency, it’s necessary to analyze the dispatching types of SAR thoroughly. Two primary dispatching patterns are discussed in this paper, central dispatch and independent search. The former refers to a central management system where target grids are selected for each SAR team, whereas the independent search means each SAR team selects target grid independently. During the process, both path selection and SAR patterns need to be analyzed so as to minimize the time spent on searching and increase the probability of finding survivors (Waugh and Streib, 2006).

Infact, in actual rescue process these two patterns are usually used in combination, and
one of them may be the major pattern according to the situation of disaster. Especially in many developing countries or remote regions, there is no unified dispatch system due to lack of information management. Independent search thus plays an important role in SAR of these regions so far. We will discuss the two patterns apart and try to analyze the difference between them clearly. Besides models and numerical examples are presented to verify the viewpoint. Few previous studies have taken the dynamic independent search into account.

2. THE PROBLEM

2.1 Basic conditions

The two patterns discussed are limited to land SAR. According to previous related researches (Waugh and Streib, 2006), the assumption has been raised that SAR teams choose their target area and paths independently. A rescue scene after rainstorm or earthquake is introduced, where part of the original roads and bridges are damaged. The rest available roads in this region are denoted as a 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 number of SAR teams searching for survivors in the region. All survivors rescued will be sent to the rescue center (node $m$) for medical treatment. This operation is set to be finished within a time period $T$, and $t \in T$ (Hu and Li, 2011).

To simplify, the network $G$ is divided into several grids, and $g$ becomes one of them ($g \in G$), so that the number of survivors in grid $g$ at time $t$ to be $S_g(t)$, and the number of survivors in zone $g$ at the initial time $S_g(1)$ are both obtained. The remaining passable paths are assumed to be not congested, and the delay caused by queue or danger is not considered in the case, which means the travel time (the time cost SAR teams from rescue center to target grid) can be guaranteed. This assumption was used in Waugh and Straub’s research (Waugh and Streib, 2006), and it helps to focus our key point on dispatching pattern selection. The travel time is spent from rescue center $m$ to grid $g$, which is constant. Let $c_{gm}$ be the travel time from rescue center $m$ to grid $g$, and $c_{mg}$ is constant.

The number of SAR teams searching for survivors remains $N$ in the network, and all teams will start from rescue center $m$ to each grid. The number of SAR teams in medical center at time $t$ is $N_m(t)$, and the number of SAR teams searching in grid is $N_g(t)$.

2.2 The general time cost of SAR

At the beginning, all SAR teams gather at the rescue center. The exact locations of survivors in each grid remain unclear. SAR teams need to choose target grids and get down to searching for survivors. The rescue cost is assumed as $C_{mg}(t)$.

The rescue work of SAR teams including three steps:

Step 1: choose target grid $g$ and head for the grid from rescue center $m$ based on the
accessible information;

Step 2: Arrive at target grid $g$ and search for survivors by cruising;

Step 3: Send the rescued survivors back to the rescue center $m$ after basic treatment.

After the survivors are sent back to the rescue center, the SAR work this round is completed, followed by the activation of a new round. It is worth noticing that the behavior patterns of Step 1 and Step 3 are different from that of Step 2. In Step 1 and Step 3, the SAR teams choose the shortest paths to their target grids, and their moves are directed routing. But in Step 2, the routes of SAR teams in target grids are independent and random.

When a SAR team arrives at grid $g$ at time $t$, the time $t_{c\mathcal{g}}(t)$ is spent finding a survivor. So the search cost for each round $C_{mg}(t)$ is the sum of travel time $c_{gm}$ (from rescue center $m$ to target grid $g$), search time $c_{g}(t + c_{mg})$ and return time $c_{gm}$ (from target grid $g$ to rescue center $m$).

$$C_{mg}(t) = c_{mg} + c_{g}(t + c_{mg}) + c_{gm}$$

Where $C_{mg}(t)$ is dispatch cost, which is the general time cost of SAR from $m$ to grid $g$. After SAR teams send the survivors back to $m$, this round of SAR task ends and a new round begins. They can either continue to search in the same grid $g$, or choose another grid to begin a new search.

3. THE CENTRAL DISPATCH AND INDEPENDENT SEARCH

3.1 The central dispatch

At the beginning of each round, SAR teams gather at $m$ and then head for the target grids. The problem needed to be solved is how to decide a target grid for each team. The situation of central dispatch could be analyzed first, in which a central management system plays a vital role. As previously assumed, the size of survivors in each grid is known, but their exact locations are not clear.

In order to successfully complete the mission, each SAR team needs to find survivors as much as possible in shortest time. SAR teams can obtain further information through modern communication facilities embedded with the central management system, which helps them to learn about the dynamic distribution of teams and make decision according to this information. It’s subsequently assumed that SAR teams have received the central dispatch orders and move to the target grids.

Central dispatch: SAR teams receive orders indicating the priority of the grid where most survivors are spotted. If SAR teams in certain grid are enough or all survivors have been found at time $t$, the central management system will prioritize the grid with second most survivors as the target; if two grids indicate the same quantity of survivors waiting for SAR
at time $t$, the system will assign the nearer one, and the rest arrangement would follow the process mentioned above.

According to these rules, in the example of Figure 1, the central management system will send SAR teams to Grid B first, and then the nearer one between the rests two would receive the SAR team first.

![Diagram](image)

**Figure 1.** Illustration graph of dispatching pattern of SAR.

### 3.2 Independent search

Although the central dispatch plays a more and more important role in SAR, the independent search is still widely applied. If there is no information management system or the system and equipment are damaged due to the disaster, the independent search will be the primary rescue pattern. In the SAR process, SAR teams are not clear about the exact location of survivors, so they have to cruise independently searching for survivors. It's significant to explore how SAR teams make decisions during the independent search, and whether difference exists between central dispatch and independent search.

**Independent search:** according to the instantaneous information about the distribution of SAR teams and survivors, SAR teams from rescue center are assigned to the grid with minimum general time cost.

The rescue cost leave for grid $g$ is $C_{mg}(t)$, and there is a positive correlation between rescue cost and the number of SAR teams, which means it will reduce the whole efficiency if there are too much SAR teams working together in one grid. Therefore, in ideal state the rescue cost of each team should be equal at time $t$,

$$C_{mg}(t) = C_{mg'}(t), \forall g \neq g'$$  \hspace{1cm} (2)

As a result, the problem has turned into a typical network distribution problem. The difference lies in that every SAR team in each round needs to select the target grid based on
the instantaneous information, and after arriving at the target grid, they will cruise search for survivors.

4. THE EXPECTED SEARCH TIME FOR SURVIVORS

The expected search time \( \mathcal{g}(t) \) in grid \( g \) at time \( t \) is presented here. If the SAR teams only estimate the search time according to current information, and both \( S_g(t) \) survivors and \( N_g(t) \) SAR teams are staying in grid \( g \) at this moment.

The survivors in the grid network are supposed to be distributed uniformly. Although the exact location is uncertain, the distribution density of survivors can still be obtained. Let the total road length be \( A_g \), and the distribution density be \( \rho_g \), so

\[
\rho_g = S_g(1)/A_g \tag{3}
\]

Where \( \rho_g \) shows the distribution density of survivors in grid \( g \). Suppose a team’s search speed to be \( v \). And after per unit time, the search distance is \( v \Delta t \), and the probability of finding a survivor is \( \rho_g v \Delta t \), so

\[
\alpha_g = \rho_g v \Delta t \tag{4}
\]

Where \( \alpha_g \) is the search parameter, suggesting the search difficulty in this grid. The less \( \alpha_g \) means a lower density of survivors’ distribution and higher search difficulty. At time \( t \), \( N_g(t) \) SAR teams remains, and after a unit time the number of survivors has been found is \( \alpha_g N_g(t) \). Those rescued survivors will be sent to the rescue center,

\[
f_{gm}(t) = \alpha_g N_g(t) \tag{5}
\]

In Eq. (5), \( f_{gm}(t) \) is the number of SAR teams back to the rescue center \( m \) from grid \( g \). It should be noted that, the quantity of SAR teams searching in grid shrinks by \( f_{gm}(t) \) at the same time, then there is

\[
N_g(t+1) = N_g(t) - f_{gm}(t) = N_g(t)(1 - \alpha_g) \tag{6}
\]

Similarly, at time \( (t+x) \),

\[
N_g(t+x) = N_g(t)(1 - \alpha_g)^x \tag{7}
\]

Now \( N_g(t+1) \approx N_g(t+x) \) 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, we have

\[
x^* = \frac{\ln N_g(t)}{\ln(1 - \alpha_g)^{-1}} \tag{8}
\]

Then we can get the expected search time \( (x^*/2) \), for a SAR team reaches grid \( g \) and search in this grid at time \( t \). \( \alpha_g \) can be obtained through survey parameters, so
\[ c_g(t) = \frac{\ln{N_g(t)}}{2\ln(\alpha_g)}^{-1} \]  

5. THE TEAM DISTRIBUTION MODEL

This section focuses on the basic process of SAR. At time \( t \), the number of SAR teams from \( m \) is \( N_m(t) \). Let the number from rescue center to each grid to be \( f_{mg}(t) \), similarly, the number of teams \( f_{gm}(t) \) back to rescue center from each grid could also be calculated. Since the number of SAR teams at the initial time is known, at time \( t \ (t > 1) \) for grid \( g \) there is

\[ N_g(t) = N_g(t-1) - f_{gm}(t) + f_{mg}(t - c_{mg}) \]  

The original number of SAR teams in grid \( g \) is \( N_g(t-1) \) at time \( t \), then \( f_{gm}(t) \) teams have spotted survivors and return to the rescue center. At the same time \( f_{mg}(t - c_{mg}) \) teams arrive at grid \( g \) and begin to search. Note that the SAR teams need to spend time \( c_{mg} \) heading for grid \( g \). The quantity of SAR teams at rescue center at time \( t \) is

\[ N_m(t) = N_m(t-1) - \sum_{g \in G} f_{mg}(t) + \sum_{g \in G} f_{gm}(t - c_{mg}) \]  

Eq. (11) shows that after subtracting the teams leaving for each grid (\( \sum_{g \in G} f_{mg}(t) \)) from the former number of teams at 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 rescue center at time \( t \). At that time the number of survivors is

\[ S_g(t) = S_g(t-1) - f_{gm}(t-1) \]  

On the basis of the discussion above, two movement models are established respectively.

**Central dispatch:** At time \( t \), the SAR teams start from rescue center \( m \) and choose the target grids according to the number of survivors in each grid. For the SAR teams from rescue center \( m \) to grid \( g \), there is

\[ N_g(t) \leq N_g(t), \text{if } f_{mg}(t) \geq 0 \]  

**Independent search:** At time \( t \), the SAR teams starting from rescue center \( m \) choose the target grids costing the minimum SAR cost that satisfies the following conditions: let \( C_m^*(t) \) be the minimum SAR cost of the SAR team from rescue center \( m \), \( C_m^*(t) = \min\{C_{mg}(t), \forall g \in G\} \). For the SAR teams from rescue center \( m \) to grid \( g \),

\[ C_{mg}(t) \leq C_m^*(t), f_{mg}(t) \geq 0 \]  

Otherwise, when \( C_{mg}(t) > C_m^*(t) \), it is indicated that the SAR teams in grid \( g \) at this time are intensive and the SAR costs are high, the SAR teams will prioritize the other grids. According to this condition, the number of SAR teams from rescue center \( m \) to each grid at time \( t \) can be obtained.
6. A NUMERICAL EXAMPLE

An example is given as following in Figure 2. The region is attacked by a flood disaster. A number of survivors in this region await to be rescued. For convenience of rescue, the region is divided into four grids labeled 1, 2, 3 and 4. M is the rescue center being closest to grid 4. At the initial time $t = 1$, there are $N$ ($N=100$) SAR teams will go to each grid to search for survivors and then bring them back to the rescue center for further treatment. The SAR teams are informed of the latest distribution of survivors through information systems. Each grid is connected by passable path and every path is bidirectional. The travel time linked two grids is manifested in Table 1.

**Table 1** Link travel time (time unit period)

<table>
<thead>
<tr>
<th>Link</th>
<th>1-2</th>
<th>2-1</th>
<th>2-3</th>
<th>3-2</th>
<th>3-4</th>
<th>4-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Link</td>
<td>1-4</td>
<td>4-1</td>
<td>1-m</td>
<td>m-1</td>
<td>4-m</td>
<td>m-4</td>
</tr>
<tr>
<td>Time</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

The number of survivors in each grid are $S_1 = 30, S_2 = 40, S_3 = 60, S_4 = 20$. Grid 1 and grid 4 is closer to M than grid 2 and grid 3. SAR teams determine the target grid based on different strategies and then choose the shortest path. Arriving at the target grid, the basic rescue time $c^r_g$ will be a time unit.

Only the corresponding selection rules is required to simulate central dispatch. As mentioned above, the nonlinear equations of independent search can be solved by network distribution method. The basic idea in this method is that a network distribution model is performed for each round. For more details, one could refer to Liu and Wang’s former research (Cho et al., 2001; Meng and Yang, 2002; Ambrosino and Scutella, 2005; Mirjazae and Moghim, 2015; Liu and Wang, 2016).

![Figure 2. Example grids of SAR](image)

Based on the conditions, the distribution of SAR teams at each moment and the change of SAR teams’ number in each grid can be calculated. For example, at the initial time, 100 SAR teams all set off for each grid to search for survivors. At this moment the distribution of SAR
teams for independent search is $f_{m1}(1) = 20$, $f_{m2}(1) = 23$, $f_{m3}(1) = 45$, $f_{m4}(1) = 12$. Therefore, at time 2, no SAR teams still stay at the rescue center because all teams are setting out for their target grids.

While for central dispatch, the initial distribution is $f_{m1}(1) = 0$, $f_{m2}(1) = 40$, $f_{m3}(1) = 60$, $f_{m4}(1) = 0$, which means the majority of SAR teams are sent to the grids where more survivors are reported. Through simulation and analysis, it has been found that all survivors are discovered and sent to $m$, which indicates how the model works.

Furthermore, the distribution of rescued survivors across time can be observed as shown in Figure 3 and Figure 4. For central dispatch, the survivors rescued from grid 3 and 2 are found to be the most in the beginning, where the most survivors are spotted. While in independent search, the distribution is more even as shown in Figure 4. Therefore, the numerical example is verified to be successful and effective by reflecting the basic objective of each strategy.

Further observation of dynamic changes in Figure 3 and Figure 4 reveals that, in the first half of the time period, the largest number of survivors rescued occurs in the independent search pattern. For example, at time 20, there are 104 cumulative survivors with independent search, whereas only 96 with central dispatch.

But since the middle of the time period, the rescued survivors’ number in central dispatch
exceeds that in independent search. Because in this case, more SAR teams in central dispatch have returned to rescue center and launch a new round of search. The simulation suggests that eventually, it takes 30 time periods in central dispatch and 28 in independent search to find all survivors. In general, the effect of independent search is better in this case, because the distribution changes in survivors and SAR teams are more comprehensively considered. The SAR travels to each grid can be obtained as shown in following Figure 5.

![Figure 5](image-url). The SAR flow distribution across time (Independent search)

7. CONCLUSION

It has been well acknowledged that the SAR in post disaster is a complex procedure with both planning and randomness. From the view of the rescue time, the paper compares the two basic rescue mode, central dispatch and independent search, with an elaboration in their rescue conditions, models and solution algorithms.

In order to improve the success rate of SAR, each SAR team needs to rescue survivors as many as possible within limited time. Now the selection of the target grid turns out to be the unsolved dispatching problem. In this paper, the shortest path priority and target grid priority are combined together to put into consideration. There are two primary dispatching pattern, central dispatch and independent search, which are much further explored in the paper for the first time. In actual SAR process the two patterns are usually adopted together, posing the difficulty to distinguish them clearly.

The numerical example result shows that the effect of independent search is better because it can coordinate SAR needs for different regions. Although the central dispatch ensures that the main rescue forces can be concentrated on the key regions, it might need to deal with the issue of unfairness. And due to the limit of uncertain information, the central dispatch easily leads to low efficiency.

In general, the effect of independent search is better because the changes in the distribution of survivors and SAR teams are fully taken into consideration. Our results are expected to be somehow helpful for designing related emergency management system and
evaluation of SAR plans.

The paper has analyzed the specific rescue moves from a new perspective but the model remains to be improved and optimized, shedding a light on the future study. For example, the factors limiting the post-disaster rescue are very complicated and arbitrary, among which the survival rate is considered to be an important one. According to the previous researches, the survival rate of survivors declines over time. In order to describe SAR process correctly, the survival rate change should be taken into account. The further study should include this factor into the model to calibrate the model. Besides, the SAR teams often share their information and cooperate with each other even in the independent search. Therefore, the future study should also pay attention to the cooperation system to improve the model to be better simulating the reality.

8. ACKNOWLEDGEMENTS

This paper was supported by Postgraduate Scientific Research and Innovation Projects of Jiangsu Province (KYCX_0512), Guangxi Science and Technology Projects (Grant No.15248002-10; Grant No.AB16380280) and Guangxi Natural Science Foundation (Grant No.2015GXNSFBA139216).

9. REFERENCES


