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EMERGENCY SUPPLY FOR MULTI-DEPOT PROBLEM IN CERTAIN AND UNCERTAIN CIRCUMSTANCES

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Abstract: It is well known that the most prominent characteristic of emergency systems is the limit of time. A scheme must be made in much shorter time, and the retrieval vehicle should be able to reach the emergency site in the earliest time according to the proposed scheme so that the emergency event is dealt with as early as possible. This paper deals with multi-depot problems in two cases: (1) When the duration or time needed by the retrieval vehicle arriving at the emergency site from each depot is a non-negative real number, a single-objective (or min-max) and a two-phase problems on the earliest-emergency-activity-start-time (EEAST) are considered. (2) When the duration is regarded as an interval number, we consider the problem of finding an optimal scheme meeting a given deadline t with maximum possibility (or truth value).

Key words: emergency systems, combination, two-phase problem, EEAST
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INTRODUCTION

Emergency services, such as emergency inventory supply, emergency medical service and fire rescue comprise a major concern of emergency planners. The strategic problem of where to locate emergency services stations (depots) and the strategic problem of the quantity of emergency resources to place in each depot were discussed in many papers (Mischael et al., 1993; Toregas, 1971; ReVelle et al., 1989). In this paper, we address the multi-depot emergency problem, which can be regarded as a second phase problem in comparison with the strategic problem. Relevant researches (Jacques, 1996; Ryusuke, 1997) mainly discussed routings, while some other researches focused on the emergency evacuation problem (Antoine, 1998; Gunnar 1998; Takeo, 1996). However, our problem appears, as an example, in emergency systems, where many depots are used to provide the materials required by the emergency site. This is a typical combinatorial problem, which can be denoted as follows:

Let $A_1, A_2, \cdots, A_n$ be n depots. With each depot A_i, we associate an available resource quantity (capability) $x_i(>0)$, $i = 1, 2, \cdots, n$. A is the emergency site, where total resource demand is x, and $\sum_{i=1}^{n} x_i \geqslant x$. Let t_i denote the duration or time needed by the retrieval vehicle arriving at A from A_i. Our first problem is finding a scheme meeting the requirement of A, which is minimum emergency-activity-start-time.

Specifically, we discuss the multi-depot problem in two cases: (1) When the duration or time needed by the retrieval vehicle arriving at the emergency site from each depot is a non-negative real number, a single-objective (or min-max) and a two-phase problem about on the earliest-emergency-activity-start-time (EEAST). (2) When the duration is regarded as an interval number, we consider the problem of finding an optimal scheme meeting a given deadline t with maximum possibility (or truth value). This paper presents some methods to solve these proposed problems. All the theorems and corresponding conclusions in this paper are original.

DEFINITION OF A SCHEME

Emergency planners are charged with making emergency schemes where two basic decisions should be included. They are,

(1) which depots to participate;

(2) how many resources provided by each selected depot.

Let φ be a scheme, which can be denoted as follows

$$\varphi = \{A_{i_1}, x'_{i_1}), (A_{i_2}, x'_{i_2}), \cdots, (A_{i_m}, x'_{i_m})\} \quad (1)$$

$0 < x'_{i_k} \leqslant x_{i_k}$, $\sum_{k=1}^{m} x'_{i_k} = x$, $i_1, i_2, \cdots, i_m$ is an arrangement of the series $1, 2, \cdots, n$, $m \leqslant n$.

According to φ, there are m depots (A_{i_1}, $A_{i_2}, \cdots, A_{i_m}$) that will provide the emergency resource, and the quantity is $x'_{i_1}, x'_{i_2}, \cdots, x'_{i_m}$ respectively. Let sub(φ) denote the set of subscripts of the depots associated with the scheme φ, Accordingly,

$$\text{sub}(\varphi) = \{i_1, i_2, \cdots, i_m\} \quad (2)$$

Let χ denote the set of all schemes with the form of φ above. In the following discussion, we assume $i_0 = 0$, $j_0 = 0$, $t_0 = 0$, $x_0 = 0$ (when necessary).

PROBLEM WITH THE DURATION BEING A REAL NUMBER

For simplicity, we assume $t_1 \leqslant t_2 \leqslant \cdots \leqslant t_n$.

Let $T(\varphi)$ denote the emergency-activity-start-time of the scheme φ. We assume that the emergency activity starts only when all required materials have reached A, or we say the emergency activity starts at the very time when the retrieval vehicles of all depots of φ have arrived at A, that is,

$$T(\varphi) = \max_{j=1,2,\cdots,m} t_{i_j} \quad (3)$$

or

$$T(\varphi) = \max_{k \in \text{sub}(\varphi)} t_k \quad (4)$$

The problem becomes

$$\min_{\varphi \in \chi} T(\varphi) \quad (5)$$

or

$$\min_{\varphi \in \chi} \max_{k \in \text{sub}(\varphi)} t_k \quad (6)$$

1. The solution of single-objective problem or min-max problem

As $t_1 \leqslant t_2 \leqslant \cdots \leqslant t_n$, there is a p ($1 \leqslant p \leqslant n$), which makes $\sum_{k=0}^{p-1} x_k < x \leqslant \sum_{k=0}^{p} x_k$ hold, let

$$\varphi^* = \{(A_1, x_1), (A_2, x_2), \cdots, (A_p, x - \sum_{k=0}^{p-1} x_k)\} \quad (7)$$

We have converted our problem to (5), which can be regarded as a single-objective problem, or (6), which is a min-max problem. Because $t_1 \leqslant t_2 \leqslant \cdots \leqslant t_n$, it is easy to see that the sum of all available materials reaching A before t_p (seeing the definition of φ^*) is smaller than x, i.e. $\sum_{k \in \{i | t_i < t_p\}} x_k \leqslant \sum_{k=0}^{p-1} x_k < x$. Accordingly, the EEAST is not later than t_p. Now $T(\varphi^*) = t_p$, we have

Theorem 1. φ^* is the optimal solution (scheme) for (5) or (6), and $T(\varphi^*) = \max_{j=1,2,\cdots,p} t_j = t_p$

Corollary 1. Any scheme φ, $T(\varphi) \geqslant t_p$ holds.

Table 1 Data for simulation $x = 50$

	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}
t_i	1	2	2	3	4	6	6	8	10	15
x_i	5	10	8	9	7	12	14	9	15	10

As an example, by Table 1., we see $\varphi^* = \{(A_1\ 5)\ (A_2\ 10)\ (A_3\ 8)\ (A_4\ 9)\ (A_5\ 7)\ (A_6\ 11)\}$ is the optimal solution for (5) or (6), and $T(\varphi^*) = t_6 = 6$

2. The solution of two-phase problem

There may be many optimal solutions (schemes) for (5) or (6). Let π denote the set of all these optimal solutions. When both cost and stability of systems are considered, finding a scheme with the smallest number of depots, is very practical.

From Theorem 1., we know that φ^* is the optimal solution for (5) or (6) and $T(\varphi^*) = t_p$. Let $N(\varphi)$ denote the number of depots involved in φ, and we consider a two-phase problem, that is,

$$\min N(\varphi)$$
$$\text{st.} \begin{cases} T(\varphi) = t_p \\ \varphi \in \chi \end{cases} \quad (8)$$

Apparently, any optimal solution for (8) is also the optimal solution for (5) or (6).

Definition 1. Given a series $x_{i_1}, x_{i_2}, \cdots, x_{i_m}$ ($i_1, i_2, \cdots, i_m$ is a certain arrangement of the series $1, 2, n$, $m \leqslant n$), if a subscript k, ($1 \leqslant k$

$\leqslant m \leqslant n$) makes $\sum_{j=1}^{k-1} x_{i_j} < x \leqslant \sum_{j=1}^{k} x_{i_j}$ hold, we call k the marginal subscript of the series x_{i_2}, $x_{i_2}, \cdots x, _{i_m}$.

Let $q = \max\{i \mid t_i \leqslant t_p, i = 1,2,\cdots,n\}$,

we have $t_1 \leqslant t_2 \leqslant \cdots \leqslant t_p = t_{p+1} = \cdots = t_q < t_{q+1} \leqslant \cdots \leqslant t_n$.

As an example given by Table 1, we see $p = 6, q = 7$.

Now, we solve the problem (8). If φ is the optimal scheme for (8), then sub(φ) is a combination of $1,2,\cdots,q$ (the supposition that there is a number $w \in \text{sub}(\varphi)$ such that $w > q$, then $T(\varphi) = \max_{k \in \text{sub}(\varphi)} t_k \geqslant t_w > t_q$, is impossible). Let $i_1, i_2, \cdots, i_q$ be the full arrangement of $1,2,\cdots, q$, which makes $x_{i_1} \geqslant x_{i_2} \geqslant x_{i_q}$ hold. Therefore, $x_{i_1}, x_{i_2}, \cdots, x_{i_q}$ is a decreasing series, and we have the following theorem.

Theorem 2. If k is the marginal subscript of the series $x_{i_1}, x_{i_2}, \cdots, x_{i_q}$, then $\varphi^{**} = \{(A_{i_1}, x_{i_1}), (A_{i_2}, x_{i_2}), \cdots\cdots, (A_{i_k} x - \sum_{j=1}^{k-1} x_{i_j})\}$ is the optimal scheme for (8) and $N(\varphi^{**}) = k$.

Proof: From the discussion above we know that if φ is an optimal scheme for (8), then sub (φ) is a combination of $\{1,2,\cdots,q\}$. It is easy to see that $N(\varphi) < k$ does not hold, because the sum of any k-1 (or fewer) elements of the series $x_{i_1}, x_{i_2}, \cdots, x_{i_q}$ will be no bigger than $\sum_{j=0}^{k-1} x_{i_j}$, further, we know $\sum_{j=0}^{k-1} x_{i_j} < x$ (since k is the marginal subscript of the decreasing series $x_{i_1}, x_{i_2}, \cdots, x_{i_q}$). That is to say, $N(\varphi) \geqslant k$. Now $N(\varphi^{**}) = k$, accordingly, φ^{**} is the optimal for (8).

An example: We use the same data in Table 1 to find the optimal solution for (8).

From Table 1, we know that $\varphi^* = \{(A_1\ 5)\ (A_2\ 10)\ (A_3\ 8)\ (A_4\ 9)\ (A_5\ 7)\ (A_6\ 11)\}$ is the optimal solution for (5) or (6), and $T(\varphi^*) = t_6 = 6$, $N(\varphi^*) = 6$.

$q = \max\{i \mid t_i \leqslant t_6 = 6, i = 1,2,\cdots,10\} = 7$

Rearrange the series A_1, A_2, A_3, A_4, A_5, A_6, A_7 according to their corresponding quantities in decreasing order, we have, A_7, A_6, A_2, A_4, A_3, A_5, A_1 (because $x_7 \geqslant x_6 \geqslant x_2 \geqslant x_4 \geqslant x_3 \geqslant x_5 \geqslant x_1$).

According to Theorem 2, $\varphi^{**} = \{(A_7\ 14)\ (A_6\ 12)\ (A_2\ 10)\ (A_4\ 9)\ (A_3\ 5)\}$ is the optimal solution for (8), and $T(\varphi^{**} = 6$, $N(\varphi^{**}) = 5$.

PROBLEM WITH THE DURATION BEING AN INTERVAL

We know that t_i denotes the duration or time needed by retrieval vehicle arriving at A from A_i, and it is regarded as a non-negative real number. In practice, a lot of information is necessary for estimating t_i, much information, however, may be uncertain. By means of interval numbers, unrealistic specifications can be avoided, and less information is needed. In fact, in many cases, it is very suitable to estimate t_i using an interval number due to many uncertain factors.

Since t_i is an interval number, we use a new symbol $\tilde{t}_i$ as the alternative of t_i, and,

$$\tilde{t}_i = [t_i^1, t_i^2],\ t_i^1 \leqslant t_i^2,\ i = 1,2,\cdots,n \quad (9)$$

It is well known that an interval number $\tilde{t}_i$ and a real number t may be incomparable in many situations (for example, when $t_i^1 < t < t_i^2$). However, we can define the truth value of the event '$\tilde{t}_i \leqslant t$', which is denoted as $T(\{\tilde{t}_i \leqslant t\})$ or $F(\tilde{t}_i, t)$.

Definition 1.1. If $t_i^1 < t_i^2$, we define,

$$F(\tilde{t}_i, t) = T(\{\tilde{t}_i \leqslant t\}) = \begin{cases} 0 & t < t_i^1 \\ \dfrac{t - t_i^1}{t_i^2 - t_i^1} & t_i^1 \leqslant t < t_i^2 \\ 1 & t \geqslant t_i^2 \end{cases}$$

Definition 1.2. If $t_i^1 = t_i^2$, we define,

$$F(\tilde{t}_i, t) = T(\{\tilde{t_i} \leqslant t\}) = \begin{cases} 0 & t < t_i^1 = t_i^2 \\ 1 & t \geqslant t_i^1 = t_i^2 \end{cases}$$

When the deadline is given, we consider the problem of finding a scheme, in which the truth value of meeting the deadline t reaches maximum.

Clearly, the truth value of the event, that the corresponding duration of any depot of φ is not bigger than t, can be used to denote $S(\varphi, t)$, the possibility of meeting the deadline t by φ, that is,

$$S(\varphi,t) = T(\bigcap_{j=1,2,\cdots,m}\{\tilde{t}_{i_j} \leqslant t\}) \tag{10}$$

or

$$S(\varphi,t) = T(\bigcap_{i\in \text{sub}(\varphi)}\{\tilde{t}_i \leqslant t\}) \tag{11}$$

By using fuzzy inference,

$$S(\varphi,t) = T(\bigcap_{j=1,2,\cdots,m}\{\tilde{t}_{i_j} \leqslant t\}) = \min_{j=1,2,\cdots,m} T(\{\tilde{t}_{i_j} \leqslant t\}) = \min_{j=1,2,\cdots,m} F(\{\tilde{t}_{i_j} \leqslant t\}) \tag{12}$$

or

$$S(\varphi,t) = \min_{i\in \text{sub}(\varphi)} F(\tilde{t}_i \leqslant t) \tag{13}$$

1. The solution of single-objective problem

Now, let us come back to our problem of finding an optimal scheme meeting the deadline t with maximum truth value, that is,

$$\max_{\varphi\in\chi} S(\varphi,t) \tag{14}$$

We use similar method to solve (14)

Let $i_1, i_2, \cdots, i_n$ be a full arrangement of $1,2,\cdots,n$ which makes $F(\tilde{t}_{i_1}, t) \geqslant F(\tilde{t}_{i_2}, t) \geqslant \cdots \geqslant F(\tilde{t}_{i_n}, t)$ hold. Let r be the marginal subscript of $x_{i_1}, x_{i_2}, \cdots, x_{i_n}$, and let φ_t $\{(A_{i_1}, x_{i_1}), (A_{i_2}, x_{i_2}), \cdots, (A_{i_r}, x - \sum_{j=1}^{r-1} x_{i_j})\}$.

Clearly, $S(\varphi_t, t) = \min_{j=1,2,\cdots,r} F(\tilde{t}_{i_j}, t) = F(\tilde{t}_{i_r}, t)$. And we have,

Theorem 3. φ_t is an optimal solution for (14), and

$$\max_{\varphi\in\chi} S(\varphi,t) = F(\tilde{t}_{i_r}, t)$$

Proof: By reduction to absurdity

If $\exists\ \varphi = \{(A_{j_1}, x'_{j_1}), (A_{j_2}, x'_{j_2}), \cdots, (A_{j_m}, x'_{j_m})\}$, which makes $S(\varphi, t) > S(\varphi_t, t)$ hold, since $S(\varphi_t, t) = F(\tilde{t}_{i_r}, t)$, we have $S(\varphi, t) > F(\tilde{t}_{i_r}, t)$, i.e. $\min_{c=1,2,\cdots,m} F(\tilde{t}_{j_c}, t) > F(\tilde{t}_{i_r}, t)$. On the other hand, $F(\tilde{t}_{i_1}, t) \geqslant F(\tilde{t}_{i_2}, t) \geqslant \cdots \geqslant F(\tilde{t}_{i_r}, t) \cdots \geqslant F(\tilde{t}_{i_n}, t)$, therefore, $\text{sub}(\varphi) \subset \text{sub}(\varphi_t)$ $(\text{sub}(\varphi) \neq \text{sub}(\varphi_t))$. Further, we know $\sum_{j=0}^{r-1} x_{i_j} < x$ (since r is the marginal subscript of the series $x_{i_1}, x_{i_2}, \cdots, x_{i_n}$), therefore, the available material of all depots of φ is less than x. Thus, φ should not be a scheme, as it results in contradiction. Therefore, φ_t is an optimal solution for (14).

2. The solution of two-phase problem

As we have discussed, there may be many optimal schemes for (14), when both cost and stability of systems are considered. Finding a better scheme among them, in which the number of depots is smallest, is very practical. That is,

$$\min N(\varphi)$$
$$\text{st.}\begin{cases} S(\varphi,t) = F(\tilde{t}_{i_r}, t) \\ \varphi \in \chi \end{cases} \tag{15}$$

Let $w = \max\{j \mid F(\tilde{t}_{i_j}, t) \geqslant F(\tilde{t}_{i_r}, t), j = 1,2,\cdots,n\}$

As we know $F(\tilde{t}_{i_1}, t) \geqslant F(\tilde{t}_{i_2}, t) \geqslant \cdots \geqslant F(\tilde{t}_{i_r}, t) \cdots \geqslant F(\tilde{t}_{i_n}, t)$. Clearly, $w \geqslant r$. Moreover, if $w < n$, then $F(\tilde{t}_{i_w}, t) > F(\tilde{t}_{i_{w+1}}, t)$.

If there is a number $v \in \text{sub}(\varphi)$ such that $v \notin \{i_1, i_2, \cdots, i_w\}$, clearly, $S(\varphi, t) = \min_{i\in\text{sub}(\varphi)} F(\tilde{t}_i, t) \leqslant F(\tilde{t}_v, t) < F(\tilde{t}_{i_r}, t)$. Therefore, if φ is an optimal scheme for (15), then $\text{sub}(\varphi)$ is a combination of $i_1, i_2, \cdots, i_w$. Let $j_1, j_2, \cdots, j_w$ be the full arrangement of $i_1, i_2, \cdots, i_w$, which makes $x_{j_1} \geqslant x_{j_2} \geqslant x_{j_w}$ hold. Therefore, $x_{j_1}, x_{j_2}, \cdots, x_{j_w}$ is a decreasing series, we have the following theorem.

Theorem 4. If e is the marginal subscript of $x_{j_1}, x_{j_2}, \cdots, x_{j_w}$, then $\phi = \{(A_{j_1}, x_{j_1}), (A_{j_2}, x_{j_2}), \cdots, (A_{j_e}, x - \sum_{k=1}^{e-1} x_{j_k})\}$ is an optimal solution for (15), and $N(\phi) = e$.

Proof: From the discussion above we know that if φ is an optimal scheme for (15), then $\text{sub}(\varphi)$ is a combination of $\{j_1, j_2, \cdots, j_w\}$. It is easy to see that $N(\varphi) < e$ does not hold, because the sum of any e-1 (or fewer) elements of the series $x_{j_1}, x_{j_2}, \cdots, x_{j_w}$ will be no bigger than $\sum_{k=0}^{e-1} x_{j_k}$, further, we know $\sum_{k=0}^{e-1} x_{j_k} < x$ (because e is the marginal subscript of the decreasing series $x_{j_1}, x_{j_2}, \cdots, x_{j_w}$). That is to say, $N(\varphi) \geqslant e$. Now $N(\phi) = e$, accordingly, ϕ is the optimal scheme for (15).

3. Illustrative examples and applications

In this section, we will give an example to illustrate the process to find an optimal solution for (15) by using the data in Table 2.

Table 2 Duration is interval number $x = 100, t = 9$

A_i	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9
$\tilde{t_i}$	[2,4]	[3,3]	[4,11]	[5,10]	[5,11]	[6,10]	[6,12]	[7,10]	[8,9]
x_i	25	21	7	10	18	14	23	25	20

Step 1. Calculate $F(\tilde{t}_i, t), i = 1, 2, \cdots, 9$; the results are shown in Table 3

Table 3 Calculation of $F(\tilde{t}_i, t)$

A_i	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9
$F(\tilde{t}_i, t)$	1	1	5/7	4/5	2/3	3/4	1/2	2/3	1

Step 2. Place the series $F(\tilde{t}_i, t), i = 1, 2, \cdots, 9$ in decreasing order, the corresponding depots are $A_1, A_2, A_9, A_4, A_6, A_3, A_5, A_8, A_7$

Clearly, $\varphi_t = \{(A_1, 25), (A_2, 21), (A_9, 20), (A_4, 10), (A_6, 14), (A_3, 7), (A_5, 3)\}$,

and $\max_{\varphi \in \chi} S(\varphi, t) = F(\tilde{t}_5, t) = 2/3$

Step 3. Clearly, $\{A_i \mid F(\tilde{t}_i, t) 2/3, i = 1, 2, \cdots, 9\} = \{A_1, A_2, A_9, A_4, A_6, A_3, A_5, A_8\}$

Arrange $x_1, x_2, x_9, x_4, x_6, x_3, x_5, x_8$ in decreasing order, the corresponding depots are $A_1, A_8, A_2, A_9, A_5, A_6, A_4, A_3$.

Therefore, $\phi = \{(A_1, 25), (A_8, 25), (A_2, 21), (A_9, 20), (A_5, 9)\}$ is an optimal solution for (15).

The truth value may be different as t changes. Especially, when deadline t less then 6, $S(\phi, t) = 0$, when $t > 10$, $S(\phi, t) = 1$. The relation between truth value and deadline can be easily found from Fig. 1.

The presented algorithm is applied in the decision support systems (DSS) of fire protection to solve the problem of the selection of multiple fire departments which are located in different areas in Nanjing City of China when a disaster is too large to be dealt with by a single department. If each path between two near intersections is denoted by an interval number, then the length of the path of two discretional intersections is also an interval, because the sum of intervals is an interval too. Accordingly, in practice, when disaster occurs somewhere, the computers, through calculation, can decide all the optimal routings from each depot to the emergency site. Under this circumstance, $\tilde{t}_i$ can be easily and rapidly derived. Thus, by using the proposed algorithm, the optimal scheme can be easily derived. Satisfactory results had been obtained through nearly one year's running since the presented algorithm was embedded in the decision support systems (DSS) of fire protection in the city.

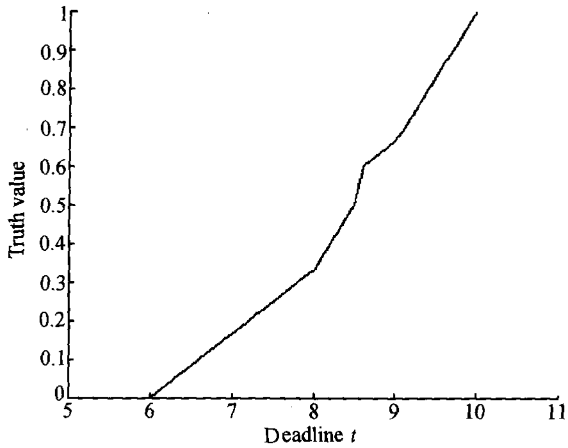

Fig. 1 The relation between truth value and deadline

CONCLUSIONS

This paper presents some algorithms for solving single-objective combination problems and two-phase problems under condition of certainty or uncertainty. The available algorithms are so simple that the optimal scheme can be obtained rapidly by computer. In this paper, t_i denotes the duration or time needed by retrieval vehicle arriving at A from A_i, which should be determined by the selected path. However, since the number of paths grows exponentially with the size of a network, the estimation of $\tilde{t}_i$ becomes more difficult, especially when the uncertain factor is concerned. Therefore, In an uncertain network, some heuristic methods may be developed to estimate $\tilde{t}_i$, and the classical shortest path algorithms such as Dijkstra algorithm and Floyd algorithm cannot be used directly as interval numbers are generally incomparable. In this paper, however, we deal with the uncertain by the interval number regarded as a special fuzzy number, so more general work should focus on the ordinary fuzzy number, and the corresponding fuzzy routing problem will be the future work in this field.

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