Sequential decision analysis of fire emergency and rescue on urban successional building fires

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Abstract

Successional building fires in cities may occur both in conventional and unconventional conditions. In the view of emergency response centers, a continuous coordinated work is requested to face (deal with) fires. In general, fires changes dynamically as situation changes, but the effects of sequential characteristic on resource scheduling were seldom considered by existing studies. The effect of fire importance on decision-making, meanwhile, was neglected in most studies. In this work, based on the whole firefighting dynamic process of fire rescue decision environment, we come out with a sequential decision making method. This method introduces the importance of different successional fires and establishes a sequential decision-making model for successional building fires with multi-rescue sources. The objective function of this method is to minimize the burned area. Case studies demonstrate the methodology and its application in fire sequential decision-making with 5 successional fires in Nanchang city. The results indicate that our method can solve problems finding sequential characteristic of successional fires and importance on decision-making.

Keywords: Successional fire; Burned area; Fire fighting; Sequential decision

Nomenclature

\begin{tabular}{|l|}
\hline
\textbf{F} & fire \\
\textbf{FE}_i & fire engines distributed to rescue F$_i$ \\
\textbf{EFE}_i & excess fire engines of F$_i$ \\
\textbf{T}_A & fire alerting time (min) \\
\textbf{T}'_a & fire engines attendance time (min) \\
\textbf{T}'_f & fire fighting suppression time (min) \\
\textbf{T}_e & fire fighting end time (min) \\
\textbf{FS} & fire station \\
\textbf{A} & burned area of successional fire (m$^2$) \\
\textbf{s}_j & the number of fire engines sent from j rescue spot to F$_i$ \\
\textbf{d}_i & the number of fire engines that F$_i$ needs \\
\textbf{A}_0 & the original burned area (m$^2$) \\
\textbf{c} & the coefficient of fire fighting importance of successional fire \\
\textbf{\mu} & fire growth rate (m$^3$/min) \\
\textbf{\alpha} & excess coefficient \\
\hline
\end{tabular}

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1. Introduction

Fire is a social disaster, so the quantity of fires and effectiveness of firefighting are significant indexes used to assess urban disaster prevention and rescue ability. The arrangement for single building fire is tactics, while the arrangements for several fires occur at the same time or during a period sequentially are strategies. All the arrangements must consider comprehensively both fire loss and distribution of fire brigades.

Multi-point fires occur easily under unconventional conditions such as earthquakes, strong breezes, warfare and terrorists. Nearly 2000 fires were triggered by the Great Kanto earthquake of Japan in 1923. However, Multi-point fires also can occur frequently under conventional conditions. Thence, some fire statistical data from 2000 to 2010 in Nanchang (Jiangxi province, China) was analyzed. Then there came the results that there were 4212 single fires and 696 multi-point fires accounting for 14.13% of the total number of fires. In this paper multi-point fires are considered as successional fires defined as new fires occurring during one period of firefighting. Compared to single fire, successional fires are more dangerous with the fire risks listed as follows:

- Successional fires have distinct time sequential characteristics and fires occur in a random sequence.
- Part of the fire fighting force may not be applied. Due to this, it may be impossible to meet the demand of new fire at early stage.
- Fire fighting in successional fires is a dynamic process which involves two changes: the development of fire and the dynamic change of available fire force.
- In order to minimize the loss caused by successional fires, a method of the optimum distribution of resources need to be developed.

In firefighting research field, Helly [1] and Chen et al. [2] systematically discussed the overall layout of fire stations and divided area problems based on fire station site selection principle, the average driving distance should be the shortest. By analyzing the fire data of Shanghai from 1992 to 1997, Han et al. [3] studied the process of rescue scheduling in cities of China, and established a model for firefighting based on non-autonomous colored petri-net method. Svensson [4] performed twenty experiments in a three-room apartment and studied tactical patterns during firefighting. He found that fires could be restrained effectively at a certain moment. By establishing dynamic models, Fiorucci [5] focused on emergency resource allocation and scheduled the whole forest fire fighting process. Jiang and Liu [6] predicted the demand of emergency resource during forest fire and proposed an optimal allocation model of resources for forest fire fighting. The objective function is to find the smallest burned area.

The emergency rescue of successional fires belongs to the field of emergency resource allocation. Gupta [7] and Shetty [8] applied game theory to solve resource allocation problems under the disaster management of multi-accident sources. Based on Shetty's work, Zhang [9] improved the model and algorithm of resource allocation of emergency rescue under conditions of multi-accident spots and multi-rescue spots, then she designed a kind of utility function based on preference (accident importance). When studying resource allocation of different simultaneous rescue tasks, Fiedrich et al. [10] established dynamic programming models to solve distribution and resource scheduling problems. According to the number of emergency source, Zhou et al. [11] divided the process of emergency resource allocation into several stages and distributed the resources using these stages by establishing models with dynamic programming methods. Wang et al. [12] proposed a dynamic optimizing method for emergency resource allocation scheme which took Markovian decision into consideration. Based on non-cooperative game theory, Wang [13] established a dynamic multi-stage decision model for emergency resource allocation and introduced penalty coefficient to diminish the influence caused by former stage on decision made at next stage. The sequential decision method can solve optimizing decision making problems randomly with a uncertain dynamic system. Yang et al. [14] introduced the sequential decision method into his research on response options of unconventional emergency. The optimal scheme of resource allocation was formed by finite and sequential games, which solved the problem of emergency resource optimal allocation due to emergency changed dynamically with time.

Although there were lots of researches on fire fighting, no one had considered the occurrence and development rule of urban building fire and the dynamic characteristics of rescue force were also not considered. The existing studies on resource scheduling during dynamic evolution process events were limited to resource scheduling for single disaster source with multi rescue source. Researchers had carried out some methods and models to study on emergency resources scheduling under multiple events and multi-point rescue. But the effects of events' sequential characteristic and importance on resource scheduling were seldom considered in these researches.

Having fully considered sequential characteristic and importance of successional fire, a sequential decision model of 'multi-point fires, multi rescue sources' was established, which combined occurrence and development characteristics and emergency rescue characteristics of building fire. The model aims to get the minimum loss of successional fires.
2. Sequential decision making method for urban successional building fires

2.1. Fundamental assumption

(1) Fire engine is the unit when assessing the emergency rescue forces. Factors such as categories of fire engines and personnel allocation are not considered.

(2) Fire emergency command system is complete and all the information related to the fire is known which includes fire growth rate, initial fire area, number of fire engines and available fire engines in fire station. What's more, the time from fire station to the successional fire spots can be figured out [9].

(3) The model does not consider small fire and supposes that general public don't participate in firefighting or their efficiency of firefighting is zero.

2.2. Firefighting decision process

This paper designs an emergency rescue process for successional fires as shown in Fig. 1 when occur by analyzing the key point in the firefighting response process in China.

Fig. 1. Fire fighting process model: fire (F), fire engines distributed to rescue Fi (FEi), fire alerting time (TA), fire engines attendance time from FEi to Fi (Ta), fire fighting suppression time (Ts), time that fire fighting end (Te), fire station (FS).

Fire emergency response center would choose and send fire engines from the nearest fire station after receiving fire alarm. The emergency response center would update the rescue command to confirm whether the rescue team went to the scheduled spot or the emerging fire spot, on condition that the new successional fire occurred before the rescue team reaching the fire spot. After 20 groups of fire extinguishment experiments, Svensson [4] came to the conclusion that there was a transition moment (we called "Ts") during the process of suppressing fire and fire was suppressed obviously. This also meant that fire rescue force excess the need. So if successional fire occurs before Ts, the current fire engines should not be adjusted. While successional fire occurs after Ts, the emergency response center will send out the excess rescue force to the new successional fire source as the new successional fire needs.

2.3. Objective function

Having applied sequential decision notion, the objective function aiming to get the minimum loss of sequential successional fire is established. Loss caused by building fires includes human lives, direct losses and indirect losses. However, these three aspects cannot demonstrate the destroy characteristics of fire completely. The statistical scholars often introduced the burned area to analyze fire damage instead [15, 16]. Considering that burned area can primely reflect the needs for fire rescue force and the effectiveness of fire rescue, we chose burned area to characterize fire loss as well.

Therefore, the objective function is set up as follows:

\[
\min \sum_{i=1}^{n} \mu_i A_i
\]

\[
\text{s.t.: } \sum_{j=1}^{m} s_{ij} \geq d_i
\]
where, \( \mu \) is the importance of successional fire \( i \), \( A_i \) is the burned area of successional fire \( i \). Meanwhile, the emergency response center must make sure that the number of fire engines sent to the \( F_i \) fire spot is more than the fire needs, \( s_j \) is the number of fire engines sent from \( j \) rescue spot to \( F_i \), \( d_i \) is the number of fire engines that \( F_i \) needs. 

\( \mu_i \) can be determined by the architectural nature, initial burned area and fire growth rate. It reflects the preferences of decision maker and the objective conditions of fires.

Stefan Särđqvist and Göran Holmstedt [15] investigated 307 non-residential buildings fires in London 1994-1997. They found that in three-quarters of the fires, the final fire area was equal to the fire area when the fire brigade arrived. The initial burned area also should not be ignored when researching the burned area. Since the initial burned area is known when the emergency response center dispatches the rescue force, it is more reasonable to consider fire growth rate and research on basis of the initial burned area. Then judge the number needed to rescue a fire.

Many researches [17, 18] indicated that during the early stages of a fire the growth in heat release rate may often be reasonably approximated by a time squared (\( t^2 \)). Class boundaries were selected as the specific values of fire growth parameter that are traditionally used to characterize slow, medium, fast and ultra-fast fire growth rates [19, 20]. Wright and Archer [21] analyzed fire data in UK in 1990s and derived relationships between the "age" of the fire and the level of average area of damage (m²). A linear regression line was fitted to the data, with the slope of the line representing the rate of damage (m²/min) produced by a delay in attendance. Occupancies were then categorized in accordance with this linear-fire growth rate. P.G. Holborn et al. [22] also claimed fire growth rate could be divided into four broad fire damage(fire loss) categories based upon the fire data between 1996 and 2000 of London. They thought that the growth rate of fire was accord with logarithm normal distribution.

On the basis of the fire statistics, burned area is in linear relationship with arrival time of fire brigade [16, 22]. Fire scale is divided into unchanged scale and expansion scale after the fire brigade arrived [16]. Peng Chen [23] indicated that burned area would not change with time of firefighting time by statistically analyzing national fires from 1995-2003 in Japan. We hypothesize that fire would not expand if fire rescue force was sufficient. So a simple model for fire development is shown in Fig. 2.

![Fig. 2. Burned area extension curve.](image)

As is shown in Fig. 2, burned area can be concluded in formula 3:

\[
A_i = A_{0i} + \alpha_i T_{i}^{a} + (1-c_i) \alpha_i \left( T_1^{a} - T_1^{o} \right)
\]

(3)

where, \( A_{0i} \) - the original burned area of fire \( i \), m², \( \alpha_i \) - fire growth rate, m²/min. \( c_i \) - the coefficient of fire fighting. Because fire rescue forces usually arrives in different time and there are no references to prove their fire fighting efficiency when the rescue forces get to the fire plot, and we propose and hypothesize it is a linear with fire rescue force when fire rescue force is over 50% [12].

\[
c_i = \begin{cases} 
0 & \frac{FE_i}{d_i} < 50% \\
\frac{FE_i}{d_i} & \frac{FE_i}{d_i} \geq 50%
\end{cases}
\]

(4)

where, \( d_i \) - the number of fire engines demanded in fire \( F_i \), \( T_1^{o} \), \( T_1^{a} \) - time that fire rescue force arrives, min.

Finally, the value of fire importance (\( \mu \)) should be set. Because the objective function is that the burned area is minimum and the most important influencing factors of burned area are initial burned area and fire growth rate. Fire importance can
be set by building categories and characteristics. The rule is shown in Table 1.

| Building categories and characteristics                                                                 | $\mu$ | Initial burned area (m$^2$) |
|-----------------------------------------------------------------------------------------------------------|-------|----------------------------|
| Warehouses (fire growth rate is very high)                                                               | 1.0   | $0 \leq A_i \leq 5$       |
| Factories, hotels, hospitals and public buildings (fire growth rate is high and casualty may be huge)    | 1.0   | $5 < A_i < 30$            |
| Licensed premises, schools, retail, further education and offices (fire growth rate is medium and casualty may be little) | 0.8   | $A_i \geq 30$            |
| Care homes and dwellings (fire growth rate is low and casualty may be little)                           | 0.5   | $0 \leq A_i \leq 5$       |
| Care homes and dwellings (fire growth rate is low and casualty may be little)                           | 1.0   | $5 < A_i < 30$            |

2.4. Scenes for successional emergency rescue

According to fire rescue process model, we can analyze emergency rescue situation respectively based on new successional fire in different alerting time.

$$T_{ii} \leq T_{d,i+1} < T_{ii}$$ (5)

For the new successional fire ($F_{i+1}$), the available rescue resource includes the fire engines ($FE_i$) that have not reached fire spot ($F_i$) and fire engines in fire station. At this time, we should consider the importance of fire ($F_i$) and fire ($F_{i+1}$). If $\mu_i \geq \mu_{i+1}$, the $FE_i$ continues to take part in the rescue of fire ($F_i$). If $\mu_i < \mu_{i+1}$, it must consider the total burned area. If $\sum_{j=1}^{n} \mu_j A_j' \leq \sum_{j=1}^{n} \mu_j A_j$, ($A_j'$ is the adjusted burned area of $F_j$), we should adjust the rescue plan, otherwise the original plan is remained.

$$T_{ii}' \leq T_{d,i+1} < T_{ii}$$ (6)

In this situation, usable emergency rescue force is the fire engines that are not sent yet. Fire engines that participate in firefighting process cannot be allocated.

$$T_{ii}' \leq T_{d,i+1} \leq T_{ii}$$ (7)

Although there are some excess fire engines due to the existence of $T'$, no further related researches get the rule of $T'$ distribution. In the actual fire fight process, the commanders can judge the $T'$ according to the fire source situation and their experiences. At this moment, excess fire engines can be chose as new emergency resources which can involve in fire fighting when not considering supply for fire engines, the physical fatigue of fire fighters and other factors. The number of excess fire engines ($EFE_i$) is determined by the intervals of typical moments in fires. As is shown in Fig. 3, $EFE_i = \beta_i FE_i$. Here $\beta_i$ represents excess coefficient changing with the process of fire fighting.

2.5. Solving steps for the objective function

(1) Considering all the available rescue forces, the set of rescue forces is: \[ \left\{ \sum_{j=1}^{m} FS_{j}, \sum_{j=1}^{n} FE_{j}, \sum_{j=1}^{l} EFE_{j} \right\} \]

(2) Form strategy set of new successional fire. Firstly, we need to confirm time matrix $T_{i+1}$ combining with the available relief forces $s_{i+1}$. Finally the possible strategy set $\phi(T_{i+1}, s_{i+1})$ is generated.
(3) Making a balance among different conflicts during fire rescue, and then solving the objective function and optimize the emergency rescue plan aiming at getting the least loss of new successional fire and original successional fires.

3. Case study

3.1. General situation of successional fire

We choose an accident in Nanchang city as research object. The data contains five successional fires occurring from 19:00 to 19:47, on January 23, 2009. Fires information is shown in Table 2 and the total burned area is 206 m². According to the fire development model, we can figure out the fire development rates in each fire by Eq. (3) as shown in Table 3. The positions of fire sources and fire stations are shown in Fig. 4. And Fig. 5 shows how the fire brigades deal with the fire in actual situation (the fire brigades did not consider fire importance and occupied fire engines). The time of each fire brigade reached the fire spot is shown in Table 4.

![Fig. 4. The positions of fire sources and fire stations.](image1)

![Fig. 5. The actual rescue decision making.](image2)

| Fire NO. | Fire NO. | Fire NO. | Fire NO. | Fire NO. |
|----------|----------|----------|----------|----------|
| F1       | 19:00    | 19:12    | 19:20    | 19:47    |
| F2       | 19:07    | 19:17    | 21:07    | 21:47    |
| F3       | 19:11    | 19:27    | 19:57    | 20:28    |
| F4       | 19:23    | 19:38    | 21:56    | 22:26    |
| F5       | 19:29    | 19:40    | 19:55    | 20:00    |

| Fire NO. | Fire growth rate (m²/min) |
|----------|---------------------------|
| F1       | 0.667                     |
| F2       | 1.714                     |
| F3       | 1.563                     |
| F4       | 1.267                     |
| F5       | 0.455                     |
Table 4. The attendance time of fire brigade fights the successional fire

| Fire Station | F1 (d=4) | F2 (d=6) | F3 (d=6) | F4 (d=4) | F5 (d=2) |
|--------------|-----------|-----------|-----------|-----------|-----------|
| FS1 (s=8)   | 12        | 10        | 7         | 19        | 15        |
| FS2 (s=9)   | 15        | 15        | 16        | 5         | 9         |
| FS3 (s=8)   | 27        | 18        | 22        | 15        | 11        |

3.2. The influence of sequential decision making method for fire rescue

Assume all fires have the same importance, and the value of $\mu$ is 1.0. We could analyze emergency rescue program respectively based on sequential decision making method. Because of $T_{d1} < T_{d2} < T_{d1}^a$, scheduling $FE_1$ to $F_2$ should be considered. With $T_{d1}^a \leq T_{d4}^a \leq T_{d1}^a$, scheduling $EFE_1$ to $F_4$ should be considered. According to the actual situation, $T_{FE_{2}}^a$ was 7 min (less than $T_{FS_{2}}^a = 10$ min) and $T_{EFE_{4}}^a$ was 3 min (less than $T_{FS_{4}}^a = 15$ min). By calculating Eq. (3), the decision making schemes were remained except $F_4$. If $EFE_1 = 2$, it should be allocated to $F_4$ firstly and then the others were allocated from $FS_2$. The rescue decision making process is as Fig. 6. After adjusting $A_i$ (the burned area) was reduced from 54 m$^2$ to 46.4 m$^2$ and the total burned area was 198.4 m$^2$.

3.3. The influence of successional fire importance for fire rescue

For successional fire, rescue decision makers have preferences when choosing the fire importance. (Assume that the importance $\mu_i$ and $\mu_j$ were larger than $\mu_i$, $\mu_k$ and $\mu_i$).

Table 5. Different value of fire importance and the corresponding burned area

| Fire | $\mu_i$ | $A_i$ (m$^2$) | $A_i'$ (m$^2$) | $A_i''$ (m$^2$) |
|------|---------|---------------|----------------|-----------------|
| F1   | $\mu_i$ | 1.0           | 28             | 33.7            |
| F2   | $\mu_i$ | 5.0           | $A_2$ (m$^2$)  | 50              | 44.6            |
| F3   | $\mu_i$ | 2.0           | $A_3$ (m$^2$)  | 54              | 54              |
| F4   | $\mu_i$ | 3.0           | $A_4$ (m$^2$)  | 54              | 46.4            |
| F5   | $\mu_i$ | 1.0           | $A_5$ (m$^2$)  | 20              | 20              |

Fire ($F_i$) happened at 19:00, fire engines ($FE_i = 4$) were sent to $F_1$ from fire station ($FS_1$). At 19:07 $F_2$ happened. For $T_{FE_{2}}^a$ was less than $T_{FS_{2}}^a$ and $T_{EFE_{4}}^a$ was less than $T_{FS_{4}}^a$. The fire engines $FE_i$ would be chose to rescue $F_2$ ($FS_1$ sent two fire engines).
engines heading for F1 and F2, the same as FS2 for F1) and fire engines \( EFE_i = 2 \) would be chose to rescue F1 (FS3 sent two fire engines heading for F1). The rescue decision making process was as Fig. 7. The value of fire importance and burned area were shown in Table 5.

When the fire importance was considered, the occupied fire engines could be fully utilized. Then the total burned area would be reduced from 206 \( m^2 \) to 198.7 \( m^2 \). Meanwhile, the burned area with different fire importance would reduce from 568 \( m^2 \) to 523.9 \( m^2 \). Decision maker can decide whether adjusting the rescue plan by our sequential decision making method or not.

4. Conclusions

In this work, successional building fire emergency rescue decision making process is established which considers the availability and scheduling principle of fire engines in the process of firefighting. The decision making process presents that the rescue force is dynamically changing, both the allocated fire engines (travelling and firefighting) and fire engines in the fire station can be dispatched by considering the need of new fire.

On the basis of the sequential characteristics of successional fire, this paper establishes a sequential decision making model aiming to get the minimum loss of successional building fire for emergency rescue. This model has half-quantitatively presented the development rules of burned area in building fire along with the time. In addition, the model also considers the fire importance when researching the effects of firefighting. According to this method, the decision maker can get the minimal burned area in the condition of considering fire growth situation and fire importance.

Focusing on a case study relevant to five successional building fires in Nanchang city, the results proved that the sequential decision making model has the capability to support the decision makers in managing complex situations, where static optimal rescue resources are occupied and different importance of successional building fires should be considered.

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