Research of Subway Emergency Resource Allocation Strategy Based on Accident Data

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Abstract. The characteristics of dense passenger flow and relatively closed operation space in urban rail transit system easily make unexpected events causing great property losses, even casualties, so emergency materials which are prepared for emergency events need rational allocation. The existing configuration methods regard each station in the network as nodes with same features, which ignore the fact that different stations have different probability of emergency events and result in limited effectiveness in saving rescue events. This work fills this gap by establishing a multi-modes emergency resource allocation based on P-medium model for minimizing the generalized cost, where the historical accident data, passenger flow, line network structure and multiply traffic modes for rescue are considered simultaneously. The concept of time value is introduced to unify rescue time and cost. A case study of some Beijing Metro networks is then carried out. The results of the solution meet the practical rescue needs. The validity of the model is verified by comparing with the existing model, which provides a methodological support for the actual emergency material allocation.

Introduction.

With the rapid development of social economy, urban rail transit is becoming more and more important in urban public transport, gradually forming a large-scale structure and network operation. The urban rail transit system may be interrupted due to various reasons, such as equipment failure, man-made attacks and so on. Operational interruption caused by emergencies will have a distinct negative impact on passengers and operation management. Accidents may damage the property and even safety of passengers. Especially under the condition of network, the complexity of passenger travel behavior increases, and the difficulty of operation management further increases. For the sake of reducing the damage from an emergency event, emergency resource is needed and calls for optimized allocation to improving operation recovery speed and reducing setup cost. Therefore, this paper mainly studies the allocation optimization of emergency resources in the network with daily accident scenarios.

The allocation of resources in emergency management includes three parts: the allocation of peacetime state, the allocation of action stage and the reverse allocation of resources after disaster. Pre-allocation is to plan the location of emergency facilities reasonably, and allocate reasonable number and types of resources at each point. In-event allocation is the dispatch and distribution of resources after disasters occur. Reverse allocation is the storage of resources after disaster stabilization. In this work, the pre-allocation is researched whose purpose is to improve the allocation effectiveness and reduce costs for sustainable resources. According to the characteristics of emergency maintenance resource allocation, the problem can further be divided into two categories: facility location problem and rescue allocation problem.

1) Facility Location Problem

Facility location problem refers to how to make reasonable location planning for emergency facilities, and allocate reasonable resources at necessary points. In 1909, the Weber first studied the location problem[1]. But at that time, the content of site selection research was not systematic, and scattered site selection research was mainly used to solve the related problems in actual production. Until 1950s, the research on emergency rescue location gradually increasd.
Shetty et al.\textsuperscript{(2)} established a resource allocation model based on the game story considering multiple selected locations. The object of the model was decreasing the emergency response time and disruption loss as much as possible and the Nash equilibrium was applied for the object to obtain the different resource allocation schemes with different accident types. Caihong Sun et al.\textsuperscript{(3)} optimized the rescue point selection and emergency resources allocation in a subway system. The networked operation and principles of resource sharing were both considered.

2) Rescue Allocation Problem

Rescue allocation problem mainly focus on the resource allocation and route allocation of emergency materials from distribution centers to multi-demand points. In detail, the relationship between distribution centers and demand points is not a single correspondence, i.e. a demand point can be serviced by not only one distribution centers and vice versa. In addition, the route and traffic mode between a distribution center and demand point pair is optional. Modi\textsuperscript{(4)} used dynamic and distributed constraints to solve the proper allocation of resources due to the dynamic and distributed nature of emergency rescue resources. Moeini et al.\textsuperscript{(5)} established a dynamic facility location model to solve the problem of ambulance configuration. The objective function of the model is to minimize uncovered demand points and transportation costs.

There are some drawbacks among the existing researches. Firstly, the objective function mainly defined as minimizing the cost, time or generalized cost of the rescue during emergency under single traffic mode scenario which was not suitable for several transport modes in reality, especially when the subway system fails because of the unexpected event. Secondly, existing researches usually assumed that the demand points were homogeneous about the disruption probability i.e. each station had the same accident probability. However, the two assumptions may conflict the realistic scenarios, especially for a subway system where accidents happened on some lines is obviously more frequent than others. Based on the above mentioned analysis, this paper bridges the gaps by developing an optimal model emphasizing fast recovery and lowest cost. The model will allocate resources optimally with minimal rescue time and cost, considering several traffic modes, various accident incidence rate and passengers loss caused by the delay.

The rest of the paper is organized as follows. Section 2 elaborates the problem studied in this paper. The methodology is developed in Section 3, and the case study are presented and discussed in Sections 4. Finally, Section 5 concludes this paper with contributions and future directions.

**Problem Description.**

The emergency resource allocation problem proposed in this section is a low incidence rate guarantee problem. There are $N$ stations in the rail transit network (transfer station is regarded as one station), where $m$ emergency stations are selected to allocate the resources needed for rescue in emergency stations. When the demand station fails, it needs emergency station to rescue it. At the same time, all stations are seems as demand stations (including emergency stations), because each station may fail. With regard to rescue mode, there are $n$ ways allowed for emergency material distribution between stations. The time and cost required to travel from emergency station $j$ to demand station $i$ through the mode $k$ are defined as $T_{kij}$ and $C_{kij}$. An upper limit of rescue time according to actual needs, which is recorded as $T_0$. Because different stations have different rescue importance value, including the location of stations in the road network, historical fault data and passenger flow characteristics, this paper considers the comprehensive rescue value $E_j$ of station $j$ in the model to improve the efficiency of emergency maintenance and the balance of resource distribution and a method will be proposed for estimate this value

**Assumption.**

To simplify the problem and construct the model properly, we assume the background and related concepts as follows.

a. The layout and management of emergency materials do not occupy much space, and general stations can be arranged, so each station is able to selected as an emergency station.
b. When the transfer station (crossover station of two lines is set up as an emergency station, two actual station is seems to be covered simultaneously. Because compared with transportation time, material transfer time in the station can be neglected.

c. The inventory of emergency materials is not considered, because the urban rail transit accident belongs to a small probability event, and two accidents can be neglected in the service scope of an emergency station.

**Notation.**

a. Decision variable

\[ x_{ij} \] the value is 1 indicating the emergency station \( j \) covers demand station \( i \), otherwise 0;

\[ y_i \] the value is 1 indicating station \( j \) is the emergency station, otherwise 0;

\[ z_{kij} \] the value is 1 indicating the emergency station \( j \) covers demand station \( i \) by the traffic mode \( k \), otherwise 0;

b. Parameter

\( i \) index of demand station;

\( j \) index of emergency station;

\( k \) index of traffic mode;

\( m \) number of emergency station;

\( N \) number of demand station;

\( I_j \) rescue value of station;

\( T_0 \) maximum emergency time acceptable;

\( VOT \) value of travel time;

\( t_{kij} \) the transportation time from emergency station \( j \) to demand station \( i \) by the traffic mode \( k \);

\( Q_i \) the passenger flow affected by the failure, that is the cross-section passenger flow of the station \( i \) where the event occurred;

\( C_m \) the cost for constructing a single emergency station;

\( C_{kij} \) the transportation cost from emergency station \( j \) to demand station \( i \) by the traffic mode \( k \).

**Model Analysis**

**The Foundation of Model Construction**

In theory, the existing location model can be summarized into the following four classical basic models.

- Collective coverage model: required to cover all demand stations, and the number of emergency base stations is the least under this condition. Maximum coverage model: the number of emergency base stations is limited, and the number of demand stations covered under this condition is the largest.
- P-median model: the number of emergency base stations is limited, under which the average time for emergency materials to reach each demand point from the nearest emergency relief station is the shortest.
- P-center model: the number of emergency base stations is limited, under which the maximum time for emergency materials to reach each demand point from the nearest emergency rescue station is the shortest.

Considering the limitations of the number of emergency stations and the maximum rescue time of demand stations, the ensemble coverage model and the maximum coverage model commonly used in resource allocation problems are not applicable. The P-center model can only optimize the longest rescue time. Therefore, this paper builds a strategy model of emergency resource allocation based on P-median model, that is, to determine the number of emergency stations according to certain restrictions, and then allocate emergency resources on the road network, while holding certain constraints.

**Rescue Value of Station**

The key of the emergency resource allocation model is the difference between stations in the network, i.e. the rescue value of each station. A method for this value is developed in this section,
which regards accident frequency and passenger flow as inherent attributes of the station, and quantifies both of them to describe the rescue value of the station in the process of emergency rescue. Different rescue values of different stations are determined to reflect the difference of rescue importance of different demand stations. By measuring the degree of network connectivity damage caused by node deletion, the importance and rescue value of network nodes can be reflected, that is, “destructiveness equals importance”. In addition to destroying the connectivity of the system, the deletion of nodes in the system will also affect some other indicators of the system. The importance of nodes can also be measured by calculating the performance changes of these indicators. One of the most common metrics is network efficiency.

According to the definition of small world network efficiency by Vito Latora, the consideration of network passenger traffic (path weight) is increased. Network efficiency can be expressed as.

$$E(G) = \frac{1}{N(N-1)} \times \sum_{i,j\in\mathbb{N}} e^{-\frac{Q_{ij}}{Q_0}}$$

(1)

where

- $E(G)$ the network efficiency of network G;
- $N$ the total number of stations in network G;
- $Q_{ij}$ the passenger flow between station i and j;
- $Q_0$ the basic inter-station passenger flow, so as to measure the level of station i-j pair inter-station passenger flow from the perspective of network;
- $d_{ij}$ the rescue distance between station i and j;
- $\beta$ the coefficient, and the influence coefficient of passenger flow on the evaluation of network efficiency.

Then, the rescue value of the station can be expressed as:

$$I_a = \frac{E(G) - E(G-a)}{E(G)} \times e^{\frac{\alpha}{P_0}}$$

(2)

where

- $P_a$ the number of accidents at Demand Station a in historical accidents;
- $P_0$ the average number of demand station accidents in historical accidents;
- $\alpha$ coefficient, the impact factor of the accident on the value of station rescue.

An example is proposed below, where values of the symbols in the upper formula are as follows. N=89, $P_a$ is set of half of maximum number of accidents and $P_0$ is the half of maximum passenger volume. By counting the passenger flow $Q_i$ and accident frequency $P_i$ of each station, the rescue value $E_j$ of each station is calculated as table 1.

<table>
<thead>
<tr>
<th>Station</th>
<th>Rescue Value</th>
<th>Station</th>
<th>Rescue Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHEGONGZHUANG</td>
<td>0.018</td>
<td>GULOUDAJIE</td>
<td>0.061</td>
</tr>
<tr>
<td>CHONGWENMEN</td>
<td>0.019</td>
<td>HUOYING</td>
<td>0.025</td>
</tr>
<tr>
<td>BEIJINGZHAN</td>
<td>0.018</td>
<td>YUXIN</td>
<td>0.016</td>
</tr>
<tr>
<td>JIANGUOMEN</td>
<td>0.033</td>
<td>XIXIAOKOU</td>
<td>0.016</td>
</tr>
<tr>
<td>CHAOYANGMEN</td>
<td>0.020</td>
<td>YONGTAIZHUA NG</td>
<td>0.017</td>
</tr>
<tr>
<td>DONGGISHITIAO</td>
<td>0.019</td>
<td>LINCUIQIAO</td>
<td>0.016</td>
</tr>
<tr>
<td>ANDINGMEN</td>
<td>0.018</td>
<td>AOTIZHONGXIN</td>
<td>0.018</td>
</tr>
</tbody>
</table>

**Objective function**

The object of the model is minimizing the sum of rescue time and transportation cost, which also can be called as generalized rescue cost shown as Eq.3. There are 3 compositions in the function. The first part denotes the total transportation cost squaring up different mode and the second part is the total cost for emergency station construction, which is liner dependence with number of emergency
stations. The residual part represents generalized cost generated by the total delay time, where the value of time denoted as VOT unifies two kind of variables.

\[
\min \sum_{i} \sum_{j} \sum_{k} C_{kij} z_{kij} x_{ij} I_j + m C_m + Q_i T_{kij} z_{kij} x_{ij} I_j VOT
\]  

**Constraints**

A maximum rescue time is defined by actual operation needs, which will limit the rescue relationship and traffic mode when rescue relationship exists. If the rescue time about one relationship and the corresponding traffic mode is large than the upper time, this relationship should not be established.

\[
z_{kij} (T_{kij} - T_0) \leq 0, \forall i, j, k
\]  

Each station should be covered by at least one emergency station, because every station has the possibility of failure hence the emergency rescue is necessary.

\[
\sum_{j} x_{ij} \geq 1
\]  

The amount of emergency station is pre-defined, i.e. the total number of selected stations should satisfy the equality constraint.

\[
\sum_{j} y_{ij} = m
\]  

Furthermore, if station j is not an emergency station \( y_{ij} = 0 \), then variable \( x_{ij} \) can only be set as 0. On the contrary, \( x_{ij} \) is random.

\[
x_{ij} \leq y_{ij}
\]  

In like manner, the relationship between \( z_{kij} \) and \( x_{ij} \) is as follows.

\[
\sum_{k} z_{kij} = x_{ij}
\]  

Finally, all the decision variable is binary.

\[
x_{ij}, z_{kij}, y_{ij} \in \{0, 1\}
\]  

We can categorize the above mentioned model as a large scale multivariate liner programming problem obviously, therefore we employ the wildly used Cplex solver to solve the problem.

**CASE STUDY**

A case based on an urban rail transit network managed by Beijing Subway Operating 3rd Company is proposed in this section. The company operates 4 lines, which are Metro Line 2, Line 8, Line 13 and Line 10. There are total 89 stations without repeat counting transfer stations.

**Model solution**

The Cplex solver is able to solve the problem accurately. When the number of emergency stations is set as 12, the results of emergency stations are shown in Table 2 and the distribution on the online network is shown in Figure 3.
Table 2 Result of Emergency Station Location

<table>
<thead>
<tr>
<th>Number</th>
<th>Emergency Station</th>
<th>Number</th>
<th>Emergency Station</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>JIANGUOMEN</td>
<td>7</td>
<td>NONGYEZHANLANGUAN</td>
</tr>
<tr>
<td>2</td>
<td>GULOUDAJIE</td>
<td>8</td>
<td>TUANJIEHU</td>
</tr>
<tr>
<td>3</td>
<td>XIZHIMEN</td>
<td>9</td>
<td>LIULIQIAO</td>
</tr>
<tr>
<td>4</td>
<td>HAIĐIANHUANGZHUANG</td>
<td>10</td>
<td>SONGJIAZHUANG</td>
</tr>
<tr>
<td>5</td>
<td>ANZHENMEN</td>
<td>11</td>
<td>BAGOU</td>
</tr>
<tr>
<td>6</td>
<td>HUIXINXIJIENANKOU</td>
<td>12</td>
<td>LONGZHE</td>
</tr>
</tbody>
</table>

Average rescue time [min] 9
Maximum rescue time [min] 19
Objective function value[yuan] 258897

Fig. 1 Distribution of Emergency Station Location

The traffic modes selected by each demand station are sorted out shown in Figure 4. The results show that 39 stations choose subway for emergency rescue, 50 stations choose cars, and no station chooses bus for emergency rescue. Although the cost by car is more expensive than the metro mode, more stations select the car mode since the speed of car is higher than that of metro which expands the rescue service area of a same station. The emergency station with low rescue value tends to be covered by this traffic mode from a farside rescue station which is in favor of reducing total emergency numbers. In addition, the bus rescue time is too long and the rescue cost is similar to that of the subway, which is not competitive.

Result and analysis

In order to prove the validity of the model, the proposed model is compared with the particle dimension adaptive model[6]. Set the same number of emergency stations as m=9. The particle dimension adaptive model adopts the step-by-step optimization method. First, cluster partition is carried out to find the minimum number of emergency stations needed, and then the location result is obtained by re-optimization in the cluster. The optimization objective is to minimize the generalized cost. The main factors considered in the model are rescue time and emergency rescue demand probability (determined by passenger flow).

Furthermore, a simplified model from the allocation facilities under multiple traffic mode (AFMM) is also modeled without considering multiple traffic mode for comparison, which is allocation facility under single traffic mode (AFSM).

To compare the location results of the three models, the rescue time of the whole network and the actual accident rescue time in 2015 are calculated. The results are shown in Table 3.
Table 3 Emergency Station Location Results

<table>
<thead>
<tr>
<th>Item</th>
<th>Particle dimension adaptive model</th>
<th>AFSM</th>
<th>AFMM</th>
</tr>
</thead>
<tbody>
<tr>
<td>PINGXIFU</td>
<td>XUANWUMEN</td>
<td>JIANGUOMEN</td>
<td></td>
</tr>
<tr>
<td>LISHUIQIAO</td>
<td>ANYIZHONGXIN</td>
<td>GULOUDAJIE</td>
<td></td>
</tr>
<tr>
<td>HAIDIANHUANGZHUANG</td>
<td>NANLUGUXIANG</td>
<td>XIZHIMEN</td>
<td></td>
</tr>
<tr>
<td>ZHICHUNLU</td>
<td>LIANGMAQIAO</td>
<td>HAIDIANHUANGZHUANG</td>
<td></td>
</tr>
<tr>
<td>HUIXINXIJENANKOU</td>
<td>PANJIAYUAN</td>
<td>ANZHENMEN</td>
<td></td>
</tr>
<tr>
<td>GUOMAO</td>
<td>JIJIAMIAO</td>
<td>HUIXINXIJENANKOU</td>
<td></td>
</tr>
<tr>
<td>XIJU</td>
<td>DAZHONGSHI</td>
<td>SONGJIAHZUANG</td>
<td></td>
</tr>
<tr>
<td>JIAOMENXI</td>
<td>LONGZHE</td>
<td>GONGZHUUFEN</td>
<td></td>
</tr>
<tr>
<td>SONGJIAZHUANG</td>
<td>WANGJINGXI</td>
<td>LONGZHE</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Average rescue time [min]</th>
<th>Maximum rescue time [min]</th>
<th>Total rescue time in 2015 [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PINGXIFU</td>
<td>14</td>
<td>34</td>
<td>157</td>
</tr>
<tr>
<td>LISHUIQIAO</td>
<td>11</td>
<td>20</td>
<td>136</td>
</tr>
<tr>
<td>HAIDIANHUANGZHUANG</td>
<td>9</td>
<td>20</td>
<td>104</td>
</tr>
</tbody>
</table>

The results show that compared with the particle dimension adaptive model, the AFSM model can reduce the average rescue time by 21.43% and the maximum rescue time by 41.18%, and the AFMM model can reduce the average rescue time by 35.71% and the maximum rescue time by 41.18%. It is of great significance to improve rescue efficiency and reduce losses.

Conclusions

A rescue resource allocation model for urban rail transit network is proposed in this paper. The model takes into account both history of accidents and the statues of network, which also includes multiple rescue traffic modes, bridging the gap about homogeneous point and single rescue mode problems in the existing researches. A method for generating rescue value based on account probability and passengers volume is first developed considering destructiveness and network efficiency. Then the allocation model for minimal generalized cost is introduced based on actual rescue need. The case study validates the model in actual scenarios and shows the superiority compared with existing method. However, this paper only studies the allocation of single emergency resources on the network. The actual emergency maintenance sometimes requires a combination of multiple maintenance resources. In the future, we still need to do further research on the establishment of joint layout of emergency relief materials.

References
