Study on emergency response model during construction of Sichuan-Tibet Railway

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Abstract. During the construction of The Sichuan-Tibet railway, there is a risk of sudden natural disasters. Rapid and effective rescue to the affected areas can reduce casualties and property losses. Based on the interval planning theory, this paper studies the emergency rescue plan in the construction of Sichuan-Tibet railway considering the coordinated rescue of various transportation modes. We constructs a two-stage model of distributing relief materials to the disaster areas and bringing the injured back to the facilities. In the first stage, the facility storage centre point responsible for rescue is decided, and the facility storage centre point opening scheme that conforms to the constraints of the actual time window is obtained. The second stage logistics vehicle distribution problem, to the disaster areas to deliver relief supplies and bring back the injured, the optimized distribution route plan. Finally, an example analysis is carried out to verify the feasibility of the model by solving GAMS.

1. Introduction

The Sichuan-Tibet Railway runs through the Hengduan Mountain range, which is prone to geological disasters, and will face extremely high safety risks during construction. When a natural disaster occurs, the construction workers in the construction area may be injured, and in severe cases, their lives may be in danger. Therefore, how to distribute supplies to the affected areas and how to plan the routes to bring back the wounded are crucial. An effective emergency response model can reduce the response time, reduce casualties and reduce property losses.

As disasters were sudden, destructive and unpredictable, in order to reduce the losses caused by disasters, relief materials must be delivered to the disaster areas as soon as possible in limited time and space. Therefore, the transportation route planning of emergency relief materials in the event of disasters has always been the focus of many scholars. Wei et al. aimed at the problem that the rescue route was not adjusted in real time according to the time-varying information of the road network, used the improved Dijkstra algorithm to find the critical value to judge when to change the rescue route, and drew the conclusion that different changes of traffic flow had different influences on the pre-selected optimal route[1]. Aiming at the problem that the shortest path is not necessarily the least time-consuming path, Cai et al. adopted the least time-consuming criterion to improve Dijkstra algorithm, and used high-precision geospatial data for simulation[2]. They proposed a real-time spatial search method based on GIS/GPS emergency system. According to the different characteristics before and after emergency rescue, Zhao Lieying divided the emergency rescue stage into emergency stage and mitigation stage, constructed the multi-objective vehicle path optimization model, and thus generated the vehicle path optimization scheme at different stages[3]. Zhu et al. proposed a route reliability measurement method for emergency rescue path planning, then built a multi-objective mathematical programming model and
designed an improved ant colony optimization algorithm to solve the problem. Taking Ludian earthquake as an example, the effectiveness of the proposed method was verified[4].

To sum up, existing literature mainly studied the route planning of emergency relief supplies under real-time information and uncertain conditions, established the route planning model under different scenarios, and designed or improved the corresponding solution algorithm[5][6][7]. However, the treatment of the wounded is rarely considered in the literature. Because the requirement of large railway construction in complex and dangerous environment for emergency rescue is different from that of traditional disaster emergency rescue, distribution of supplies and bringing back the wounded should be considered together.

2. Model building
This section mainly includes the establishment process of Sichuan-Tibet railway emergency rescue model, including applicable scenarios, assumptions and model content.

2.1. Problem description
The problem studied in this paper is described as follows: when natural disasters occur during the construction of Sichuan-Tibet railway, the construction personnel in the construction area will be harmed. A two-stage model based on interval planning was established to deliver relief supplies and bring the wounded back to the affected areas. In the model, five modes of transportation are considered for coordinated rescue, namely, small truck, medium truck, helicopter, military helicopter, train and truck connection. Relief supplies are divided into two categories, namely emergency relief supplies and ordinary relief supplies. Emergency supplies are demanding faster access to the affected areas. The severity of the wounded can be divided into three categories: lightly wounded, severely wounded and critically wounded. Different types of wounded persons have their own time window, and the rescue time window for seriously wounded persons is smaller. The first stage of the model aims at minimizing the opening cost of the facility storage centre and decides the opening facility storage centre. The second stage of the model aims at minimizing the cost of material transportation and the cost of bringing back the wounded.

2.2. Model assumes
The coordinates of each facility storage centre and the disaster point are known. The number of casualties of each category in each disaster point does not exceed the maximum loading capacity of the means of transport. The demand for each type of materials in each disaster point does not exceed the maximum loading capacity of the means of transport. The number of vehicles at the facility storage centre is limited. It is assumed that all types of vehicles have no maximum travel distance and travel at a constant speed during the rescue. Each type of vehicle leaves from the facility storage centre and returns to the original facility storage centre upon completion of the mission.

2.3. Model content
An emergency response network during the construction of Sichuan-Tibet railway directed road network diagram $G=(V,D)$ is constructed, where $V = \{1,2,3...n+1,n+2...,n+h,..,n+H\}$, $n$ is the number of disaster points, $h$ is the number of facility storage centres, $H$ is the number of each facility storage centre, and $D$ is the arc set between two points in the road network.

Indices and Sets:
$i$ : index of point in the road network;
$j$ : index of point in the road network;
$k$ : set of means of transport, $K$ is the total number of vehicles at all facilities.
$l$ : set of casualty types, $l=1,2,...,L,L=3$;
$p$ : set of the types of materials required, $p=1,2,...,P,P=2$;
$V'$: when $i \in [1, n]$, means that this node is the disaster point and $V' \in V$;

$V_0$: set of facility storage centres, when $n = 0$, node $V_0 = \{h | h = 1, 2, 3 ... H\}$ is facility storage centres;

Parameters:

$s_{i,j}$: the distance from node $i$ to node $j$;

$v_h$: the driving speed of the means of transport at facility storage centre $h$, $h \in V_0$;

$d_{i,l}'$: estimate the number of $l$ casualties in the disaster point $i$, $l = 1, 2, ..., L$, $L = 3$, $i \in [1, n]$;

$d_{i,p}'$: estimate the number for supplies $p$ in the disaster point $i$, $p = 1, 2, ..., P$, $P = 2$, $i \in [1, n]$;

$d_{i,l}$: the number of $l$ casualties in the disaster point $i$, casualties is an interval number, where $d_{i,l}^U$ is its upper bound, $d_{i,l}^L$ is its lower bound, $d_{i,l} = [d_{i,l}^L, d_{i,l}^U]$;

$d_{i,p}$: the number for supplies $p$ in the disaster point $i$, supplies is an interval number, where $d_{i,p}^U$ is its upper bound, $d_{i,p}^L$ is its lower bound, $d_{i,p} = [d_{i,p}^L, d_{i,p}^U]$;

$C_{1h}$: the fixed cost of facility storage centre $h$ means of transportation, fixed cost is related to the mode of transportation, $h \in V_0$;

$C_{2h}$: facility storage centre $h$ transportation vehicle per unit distance travel cost, $h \in V_0$;

$Q_{h,l}$: maximum load of casualties $l$ transported by means of facility storage centre $h$, maximum load is related to the mode of transportation, $l = 1, 2, ..., L$, $L = 3$, $h \in V_0$;

$Q_{h,p}$: maximum load of supplies $p$ transported by means of facility storage centre $h$, maximum load is related to the mode of transportation, $p = 1, 2, ..., P$, $P = 2$, $h \in V_0$;

$t_{ij}'$: deployment time of means of transport at facility storage centre $h$, $h \in V_0$;

$TW_i$: the upper limit of the time window of casualties $l$;

$\delta_{h,k}$: 0-1 binary variable, $\delta_{h,k} = 1$ indicates that vehicle $k$ is at facility storage centre $h$; $\delta_{h,k} = 0$, otherwise, $h \in V_0$, $k \in K$;

$R_h$: service/cover radius of facility storage centre $h$, $h \in V_0$;

First Stage Decision Variables:

$y_h$: 0-1 binary variable, $y_h = 1$, if the facility storage centre is opened at node $h$; $y_h = 0$, otherwise, $h \in V_0$;

$x_{i,h}$: 0-1 binary variable, $x_{i,h} = 1$, if the disaster point $i$ can be covered by facility storage centre $h$; $x_{i,h} = 0$, otherwise, $h \in V_0$, $i \in V'$;

Second Stage Decision Variables:

$z_{i,j,k}^k$: 0-1 binary variable, $z_{i,j,k}^k = 1$, if vehicle $k$ at facility storage centre $h$ is going from node $i$ to node $j$; $z_{i,j,k}^k = 0$, otherwise, $h \in V_0$, $k \in K$;

$e_{i,j,k,p}^k$: the number of class $p$ supplies that vehicle $k$ transport from node $i$ to node $j$, $p = 1, 2, ..., P$, $P = 2$, $k \in K$;
\( e_{i,j}^k \): the number of class \( l \) casualties that vehicle \( k \) transport from node \( i \) to node \( j \), \( l=1,2,\ldots,L, L=3, k \in K \).

The objective function can be presented as the sum of the fixed-operation cost (first stage of preparation) and the supply transportation cost (second stage of disaster response) for the emergency management, as follows:

\[
\min \sum_{h \in V_0} C_{i,h} y_h + Q(y, x, d, u)
\]

S.T.

\[
y_h \geq x_{i,h}, \forall i \in V', h \in V_0
\]

\[
\sum_{h \in V_0} y_h \geq 1
\]

\[
N(i) = \{ h \in V_0 | x_{i,h} \leq R_{i,h}, \forall i \in V' \}
\]

\[
\sum_{h \in V_0} x_{i,h} Q_{h,p} \geq d^p_{i,j}', \forall i \in V', p \in P
\]

\[
\sum_{h \in V_0} x_{i,h} Q_{h,j} \geq d_{i,j}', \forall i \in V', j \in L
\]

\[
y_h \in \{0,1\}, \forall h \in V_0
\]

\[
x_{i,h} \in \{0,1\}, \forall i \in V', h \in V_0
\]

The second stage objective includes the supply transportation cost, with the detailed objective expression and constraints as follows:

\[
Q(x,y,d,u) = \min \sum \sum_{k=1}^{K} x_{i,k,h} S_{i,j,k} C_{i,j,k} \delta_h^k
\]

S.T.

\[
\sum_{k=1}^{K} \sum_{i,j,h}^k \delta_h^k \geq 1, \forall j \in [1,n], h \in V_0
\]

\[
\sum_{k=1}^{K} \sum_{i,j,h}^k \delta_h^k - \sum_{k=1}^{K} \sum_{i,j,h}^k \delta_h^k = 0
\]

\[
\sum_{j=1}^{n} \sum_{i,j,k}^k d_{i,j}^p, d_{i,j}^R \delta_h^k \leq Q_{h,p}, \forall p = 1,2,\ldots,P
\]

\[
\sum_{j=1}^{n} \sum_{i,j,k}^k d_{i,j}^l, d_{i,j}^R \delta_h^k \leq Q_{h,l}, \forall l = 1,2,\ldots,L
\]

\[
\sum_{h=1}^{n} \sum_{i,j,k}^k z_{i,j,h} \delta_h^k = z_{i,j,h}, \forall h \in V_0, k \in K
\]

\[
\sum_{p=1}^{n} e_{i,j,p} \leq [u_{i,j}^l, u_{i,j}^R], \forall (i,j) \in V, k \in K
\]

\[
z_{i,j,k}^h \leq y_h, \forall (i,j) \in V, k \in K, h \in V_0
The objective function (1) minimizes the total cost. Constraint (2) and (18) ensures that the disaster point is covered by open facility storage centre. Constraint (3) and (4) ensures that a facility storage can satisfy at least one of the disaster point it covers. Constraints (5) and (6) is to meet the estimated needs of supplies and bring back the wounded. Constraint (10) ensures that the disaster point is covered. Constraint (11) means that each vehicle must leave after serving one disaster point and serve the next disaster point. Constraint (12) represents the load of the same vehicle at the previous point minus the material requirements at the next point. Constraint (13) represents the carrying capacity of the same vehicle at the next point minus the carrying away injured person at the last point whose carrying capacity is at the last point. Constraint (14) and (15) means that the maximum load of the vehicle does not exceed the rated load. Constraint (16) means that there is no task of mutual distribution between facility storage centres, and the vehicle will return to the original facility storage centre immediately after the completion of distribution. Constraint (17) is the path capacity limit. Constraint (19) ensures that relief supplies arrive the disaster point within the time window.

3. Example Analysis

The emergency rescue network in the construction process of Sichuan-Tibet Railway is constructed, as shown in Figure 1. It includes 5 disaster points and 10 facilities.

Figure 1. The simulation road network.

The demand for supplies and the number of injured persons in each affected area are expressed by interval Numbers, among which the number of critically injured persons is known. The specific values are shown in Table 1. When the interval number takes the lowest value and the interval number takes the highest value, they are solved respectively. The solution results show that the rescue cost is between [14276 16438] while the time window is guaranteed. When the interval number takes the lowest value at the same time, the route of material transportation and bringing back the wounded is 7-1-3-7,8-2-4-5-8,10-1-4-10,13-3-5-13.
Table 1. Parameter input.

| Disaster point | 1     | 2     | 3     | 4     | 5     |
|----------------|-------|-------|-------|-------|-------|
| Minimum supply demand | 12.16 | 15.6  | 12.26 | 12.26 | 9.6   |
| Maximum supply demand   | 18.26 | 27.14 | 18.20 | 15.30 | 15.16 |
| Minimum number of casualties | 4,5,3 | 5,3,0  | 4,7,6  | 4,8,5  | 3,1,2 |
| Maximum number of casualties | 6,10,3 | 9,7,0 | 6,8,2 | 5,10,5 | 5,6,2 |

It can be seen from the solution results that under the condition of meeting the material needs, the model selects the transportation mode of transporting the wounded through the time window constraint. The critically ill are removed by a fast means of transportation (such as aircraft), and the less severely injured are considered to be the least costly to meet the rescue time window. This also reflects the role of the model, which can ensure effective rescue without excessive waste of resources.

4. Conclusion

Based on the interval planning theory, a two-stage emergency response model of multi-mode coordinated rescue is established in this study. Relief supplies were distributed to the affected areas and the injured were brought back to the facilities. In the model, various emergency supplies and various types of casualties are considered, which more in line with the reality is. The applicability of the model is verified by example analysis, which can provide reference for emergency response in the construction of Sichuan-Tibet railway.

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References

[1] Wei X G, Lv W, Song W G. (2013) Rescue route reselection model and algorithm for the unexpected accident. Procedia Engineering, 62.
[2] Cai M, Deng Y J, Tang Z R. (2010) An optimal spatio-temporal path algorithm for urban emergency rescue. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 38.
[3] Zhao L Y. (2016) Study on vehicle path Optimization in different stages of natural disaster emergency rescue, Beijing Jiaotong University.
[4] Zhu J M, Liu S Y. (2019) Smita Ghosh. Model and algorithm of routes planning for emergency relief distribution in disaster management with disaster information update. Journal of Combinatorial Optimization, 2019, 38(1): 208–223.
[5] Hong X, Lejeune M.A, Noyan N. (2015) Stochastic network design for disaster preparedness, IIE Transactions, 47(4), 329-357.
[6] Li A, Nozick L, Xu N, Davidson R. (2012) Shelter location and transportation planning under hurricane conditions. Transportation Research Part E, 48(4), 715-729.
[7] Ortiz-Astorquiza C, Contreras I, Laporte G. (2019). An exact algorithm for multilevel uncapacitated facility location. Transportation Science, 53(4), 1085-1106.