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Dynamic traffic flow-based post-earthquake road network restoration and relief logistics

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Abstract. Earthquake often accompanies a large-scale road network damaged in the disaster area. Right to repair this road network is crucial to post-earthquake emergency relief efforts. Therefore, the author first develops a bi-level programming model to get optimal road network repair sequence based on dynamic traffic flow at the upper level and obtain success of relief materials allocation and the routes of emergency relief vehicle at the lower level. Then, a stable hybrid genetic algorithm is designed to deal with this non-convex mixed-integer programming model. Finally, the proposed methodology is validated by a benchmark road network, Sioux-Falls network, which is abstracted from the Northridge earthquake. The results demonstrate that the applicability and usefulness of the presented approach and have the advantages of assisting the decision-makers in determining road network repair sequence and relief materials allocation and the routes of emergency relief vehicles.

Key words. Road network restoration, relief logistics, stable hybrid genetic algorithm.

1. Introduction

Earthquake as one of mentioned natural disaster, which often causes huge property losses, such as damaged road network, buildings. Unfortunately, this type of disaster happened frequently over the past few years [1]. Therefore, deploying an emergency relief efforts immediately is the key to cut down the losses. In the post-earthquake emergency response phase, the two most important intervention activities are the evacuation of people and the delivery of materials. Evacuation takes place during the initial phase of emergency response in order to transfer the injured people out of the affected areas. Delivery of materials (relief logistics) activities will

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be continued for a longer period of time to provide necessary relief materials to people remain in the affected areas, which can substantially reduce. Therefore, many researchers focused on relief logistics activities [2][3][4]. However, they were only considered single relief commodity distribution problem and ignored the influences on damaged road network [5]. Therefore, there are a great number of researches began to study the post-earthquake road network repair schedule problem, i.e., [6] established a fuzzy multiple workgroups multiple objectives simulation model to describe the road network repair work scheduling problem. [7] developed a multiple objectives schedule model of highway emergency repair after earthquake attacks. [8] proposed a mathematical model of seismic emergency repair to reduce the maximum number of affected people and to repair the maximum kilometers of open roads. [9] developed a time-space network model to minimize the total required time of road network repair. [10] proposed a work team routing or scheduling model incorporated with the stochastic required time of traveling and repairing. [11] developed a mathematical optimization model that considered larger-scale supply-demand perturbations to determine the sequence of road network repair. [12] utilized rolling-horizontal modeling technique and stochastic programming method to formulate a real-time emergency rehabilitation scheduling model with stochastic duration time. [13] designed an ant colony system-based hybrid algorithm to solve the road network repair problem based on time-space network flow. [14] addressed one repair crew scheduling and routing problem to optimize the accessibility of the towns or villages that demand humanitarian relief.

There are also some researches attempted to provide mathematic models for improving road network serviceability by incorporating with road network repair and relief logistics. [15] developed a bi-level programming model to describe the road network repair problem for restoring the road network to meet the time constraints associated with emergency rescue and evacuation. [16] and [17] proposed a dynamic path-based mathematic model to identify the critical blockages and then clean them with limited resources.

Though the researches mentioned above formulated a road network repair mathematic model to right improve the road network serviceability to meet the relief materials within limited time requirements, they didn't consider the connection between dynamic traffic flow and road network repair. Provide that there is some damaged block completed repaired, the path of evacuation, relief logistics, and civilians' traveling would be changed. In order to elaborate clearly the relationship between dynamic traffic flow and road network repair, we first develop a bi-level programming model to minimize the total repair time based on dynamic traffic flow at the upper level, and to maximize the satisfaction of relief allocation as well as minimize the total travel time of delivering relief materials at the lower level. Then, a stable hybrid genetic algorithm is designed to solve this model due to this model has been demonstrated to be a non-convex mixed-integer programming model. Finally, we utilize a benchmark road network, Sioux-Falls network, which derived from the Northridge earthquake to validate the reliability and validity of the proposed model and algorithm. The results of this numerical example and some conclusions are provided at the end of this paper.

2. Problem Description, Assumption and Model

In the event of an earthquake, many road sections may be damaged and many paths have to be alternated. Obviously, to repair the damaged block immediately is very important to improve the road network serviceability to short the travel time of delivering relief materials from distribution centers (DCs) to affected areas (AAs) and the travel time of transferring the injured people out of the affected areas to the safe places, such as hospitals, shelter places and schools, so that the losses incurred by earthquakes would be decreased. However, which damaged block should be repaired first? How much travel time of logistics or evacuations activities shorted? The next damaged block should be repaired is? In this paper, the author calls these questions as *post-earthquake relief logistics and road network repair scheduling problem*, abbreviated as PERLRNRSP. The core to solve PERLRNRSP is to determine the sequence of road network repair, which usually is taken by traffic management agency or rescue command centers at the upper level mainly to restore the basic function of the road network. Whereas the relief logistics decisions at the lower level, which are made by the managers of distribution centers and mainly to minimize the total required time to deliver relief materials to affected areas and to maximize the satisfaction of relief allocation.

Therefore, the author develops a bi-level programming model to minimize the total required time for road network repair based on dynamic traffic flow to generate an efficient road network repair sequence at the upper level and to minimize the total time of delivering relief materials to affected areas and to maximize the satisfaction of relief allocation to get a success of relief logistics decisions at the lower level.

Giving a planning horizon T. $G(N, A)$ denotes a road network, where N denotes the set of nodes, $i, j \in N$, which also represents the set of traffic analysis zones, including: (a) the set of damaged blocks that required to be repaired N_r, d, b, k as the index, (b) the set of distribution centers N_s, m as the index, (c) the set of affected areas N_d, n as the index, and (d) the set of repair workstations N_w, w as the index, and has $|w_g|$, $w_g \subset WG$, workgroups, where WG represents the set of workgroups, if the workgroup g belongs to w_g then $p_{wg} = 1$, else $p_{wg} = 0$. And A represents the set of arcs $a = (i, j) \in A$, $i \neq j$, $i, j \in N$. In addition, we use (t_d^a, t_d^b, t_d^c) to denote the required time for repairing damaged block d and $(ST_d, LT_d]$ represents time window, where ST_d represents the start time, which usually set to zero during the post-earthquake response phase, and LT_d denotes the time that the damaged block has to be repaired; c_a denotes The capacity of arc a; f_a represents the traffic flow traverses through the arc a; t_a expresses the required travel time to cross the arc a, which can be calculated by BPR (Bureau of Public Roads) function $t_a = t_a^0 \cdot \left(1 + \alpha \cdot (f_a/c_a)^\beta\right)$, where t_a^0 denotes the required travel time under free traffic flow, α and β are the regression parameters, usually, $\alpha = 0.15$, $\beta = 4$; t_{dbg} denotes the required travel time for workgroup g migrating from damaged block d to b; c_{w1g} expresses the required travel time for workgroup g traveling from workstation w to the first assignment; O denotes the set of origin, r as the index; D expresses the set of destination, s as the index; Q_{rs} denotes the traffic demand for OD pair rs; S_{rs} to denote the set of available travel path for pair rs; z_{rs}^p represents the users whether select the path $p \in S_{rs}$ or not, if yes, then $z_{rs}^p = 1$, else $z_{rs}^p = 0$; $\delta_{rs}^{a,p}$ or $\delta_{rs}^{(i,j),p}$ denotes whether the travel path contains the arc a or not, if yes, then $\delta_{rs}^{a,p} = \delta_{rs}^{(i,j),p} = 1$, else $\delta_{rs}^{a,p} = \delta_{rs}^{(i,j),p} = 0$; (D_n^a, D_n^b, D_n^c) denotes the required relief materials for affected area n; S_m expresses the number of relief materials that can be supplied by distribution center m; V expresses the type of relief vehicles set (i.e., camion, truck, and bus), v as the index; Q_v denotes the capacity of type v relief vehicle; NUM_v denotes the number of type v emergency relief vehicle available; T_{mnv} denotes the required travel time from distribution center m to affected area n by the type of v relief vehicle; SUS_{mnv} expresses the required delivery times from distribution center m to affected area n by the type of v emergency relief vehicle; SUV_{mnv} denotes the required number of v type of emergency relief vehicle from distribution center m to affected area n; B is big positive number; x_{dg} denotes whether the damaged block d to be repaired by workgroup g or not, If yes, then $x_{dg} = 1$, else $x_{dg} = 0$; A_{mn} is the number of relief materials to be allocated to affected area n from distribution center m; y_{dbg} denotes whether the workgroup g after repairing damaged block d and then forward to repair damaged block b or not, if yes, then $y_{dbg} = 1$, else $y_{dbg} = 0$; o_m denotes whether the distribution center m is opened or not, if yes, then $o_m = 1$, else $o_m = 0$; w_{mnv} denotes whether the affected area n is serviced by distribution center m by type of emergency relief vehicle v or not, if yes, then $w_{mnv} = 1$, else $w_{mnv} = 0$.

Upper-level problem formulation (roadway restoration scheduling)

The objective of the upper level is to minimize the total required road network repair time that showed in (1), which includes the required travel time for workgroup (partition 1) and the required repair time for all damaged blocks (partition 2).

$$Z_1 = \min \underbrace{\sum_{d \in N_r} \sum_{b \in N_r} \sum_{g \in WG} t_{dbg} \cdot y_{dbg} + \sum_{g \in WG} c_{w1g} \cdot p_{wg}}_{1} + \underbrace{\sum_{d \in N_r} \sum_{g \in WG} E(t_d) \cdot x_{dg}}_{2} \quad (1)$$

Subject to:

$$\sum_{g \in WG} x_{dg} \leq 1, \forall d \in N_r \quad (2)$$

$$\sum_{d \in N_r} \sum_{b \in N_r} \sum_{g \in WG} y_{dbg} - \sum_{b \in N_r} \sum_{k \in N_r} \sum_{g \in WG} y_{bkg} \leq 1 \quad (3)$$

$$\sum_{d \in N_r} \sum_{b \in N_r} \sum_{g \in WG} y_{dbg} \leq 1 \quad (4)$$

$$LT_b \geq [LT_d + \mathrm{E}(t_b) + t_{dbg}] \cdot y_{dbg} + B \cdot (1 - y_{dbg}), \forall g \in WG, \forall d, b \in N_r \quad (5)$$

$$ST_b \leq [LT_d + t_{dbg}] \cdot y_{dbg} + B \cdot (1 - y_{dbg}), \forall g \in WG, \forall d, b \in N_r \quad (6)$$

$$\sum_{r\in O}\sum_{s\in D}\sum_{j:(i,j)\in A} f_{(i,j)}\cdot\delta_{rs}^{(i,j),p}\cdot z_{rs}^{p}-\sum_{r\in O}\sum_{s\in D}\sum_{j:(j,i)\in A} f_{(j,i)}\cdot\delta_{rs}^{(j,i),p}\cdot z_{rs}^{p}=\begin{cases} Q_{rs}, i=r\\ 0, i\notin\{r\}\cup\{s\}\\ -Q_{rs}, i=s\end{cases} \tag{7}$$

$$\sum_{r\in O}\sum_{s\in D}\sum_{j:(i,j)\in A} f_{(i,j)}\cdot\delta_{rs}^{(i,j),p}-\sum_{r\in O}\sum_{s\in D}\sum_{j:(j,i)\in A} f_{(j,i)}\cdot\delta_{rs}^{(j,i),p}=\begin{cases} f_{(i,j)}, i=r\\ 0, i\notin\{r\}\cup\{s\}\\ -f_{(i,j)}, i=s\end{cases} \tag{8}$$

$$\sum_{r\in O}\sum_{s\in D}\sum_{j:(i,j)\in A}\delta_{rs}^{(i,j),p}-\sum_{r\in O}\sum_{s\in D}\sum_{j:(j,i)\in A}\delta_{rs}^{(j,i),p}=\begin{cases} 1, i=r\\ 0, i\notin\{r\}\cup\{s\}\\ -1, i=s\end{cases},\quad \sum_{j:(i,j)\in A}\delta_{rs}^{(i,j),p}\le 1 \tag{9}$$

In (1), where $E(t_d)=(t_d^a+2t_d^b+t_d^c)/4$ denotes the expected repair time for a damaged block d [18], and (2) ensure that a damaged block can accessed by no more than repair workgroup, (3) and (4) denote that when the damaged block has been repaired, the workgroup has to leave to go to next damaged block until the last damaged block repaired, (5) denote the relationship between the repair completion times between damaged block d and damaged block b, (6) denote the real-time for beginning repairing damaged block b, means the rescue machinery, fuel, and other resources are delivered to the damaged block should be earlier than the time window, where the value of t_{dbg} determined by the path of workgroup g from damaged block d to damaged block b. The required travel time of each link of the path can be computed by the BPR function, where the traffic flows traverse this link f_a determined by dynamic traffic flow. In this paper, we assume that the traffic flows generate from not only the relief logistics but also the civilian evacuation, moreover, the traffic flows should keep balance, which includes the balance between original traffic analysis zone and destination, which can found in (7) and the balance for arc a, means the flows enter into the start point of this link should leave from the end point of the same link, which showed in (8) and (9) denote continuous travel path, means the users enter into the arc/link should leave this arc/link until the users reached the destination.

The main purpose of the lower level is to deliver the relief materials to affected area as soon as possible associated with maximum satisfaction to relief allocation.

Lower level problem formulation (relief logistics)

$$Z_2=\min\sum_{m\in N_s}\sum_{n\in N_d}\sum_{v\in V} SUS_{mnv}\cdot T_{mnv}\cdot w_{mnv} \tag{10}$$

$$Z_3=\max\min\left\{\sum_{m\in N_s} A_{mn}\Big/E(\widetilde{D}_n)\right\} \tag{11}$$

Subject to:

$$\sum_{m\in N_s} A_{mn} = \sum_{m\in N_s}\sum_{v\in V} SUV_{mnv}\cdot SUS_{mnv}\cdot Q_v\cdot o_m, \forall n\in N_d \tag{12}$$

$$0 < \sum_{m\in N_s} A_{mn} \le E(\widetilde{D}_n), \forall m\in N_s \tag{13}$$

$$\sum_{n\in N_d} A_{mn} \le S_m\cdot o_m, \forall m\in N_s \tag{14}$$

$$w_{mnv} \le o_m, \forall m\in N_s, \forall n\in N_d, \forall v\in V \tag{15}$$

$$T_{mnv} = \sum_{m\in N_s}\sum_{n\in N_d}\sum_{a\in A}\delta_{mn}^{a,p}\cdot z_{mn}^{p}\cdot t_a, \forall v\in V \tag{16}$$

$$\sum_{m\in N_s}\sum_{n\in N_d}\sum_{j:(i,j)\in A}\delta_{mn}^{(i,j),p}\cdot f_{(i,j)}\cdot z_{mn}^{p} - \sum_{m\in N_s}\sum_{n\in N_d}\sum_{j:(j,i)\in A}\delta_{mn}^{(j,i),p}\cdot f_{(j,i)}\cdot z_{mn}^{p} = \begin{cases} A_{mn}, i=m \\ 0, i\notin\{m\}\cup\{n\} \\ -A_{mn}, i=n \end{cases} \tag{17}$$

$$\sum_{m\in N_s}\sum_{n\in N_d}\sum_{j:(i,j)\in A} f_{(i,j)}\cdot\delta_{mn}^{(i,j),p} - \sum_{m\in N_s}\sum_{n\in N_d}\sum_{j:(j,i)\in A} f_{(j,i)}\cdot\delta_{mn}^{(j,i),p} = \begin{cases} f_{(i,j)}, i=m \\ 0, i\notin\{m\}\cup\{n\} \\ -f_{(i,j)}, i=n \end{cases} \tag{18}$$

$$\sum_{m\in N_s}\sum_{n\in N_d}\sum_{j:(i,j)\in A}\delta_{mn}^{(i,j),p} - \sum_{m\in N_s}\sum_{n\in N_d}\sum_{j:(j,i)\in A}\delta_{mn}^{(j,i),p} = \begin{cases} 1, i=m \\ 0, i\notin\{m\}\cup\{n\} \\ -1, i=n \end{cases} \tag{19}$$

Where (10) represents to minimize the total travel time for delivering relief materials. (11) to maximize the satisfaction of allocating the relief materials, where A_{mn} can be calculated by (12). Practically, the relief materials in distribution centers are not enough to satisfy all of the affected areas' demand, which are shown in (13). The relief materials supported by distribution centers should not beyond their supplies as showed in (14). In addition, (15) denotes that the relief vehicles can't assign to a closed distribution center. (16) denotes the required travel time from distribution centers to affected area through the shortest path, means the relief vehicles also should follow the user equilibrium, means that the traffic flow generated by relief vehicles is a part of traffic demand. Therefore, the delivered relief flow balance, which is shown in (17). The (18) is the flow balance constraint for relief vehicles, and (19) is to ensure the relief vehicle travel path's continuity.

3. Model Analysis and Solution

In this section, we proposes a stable hybrid genetic algorithm to the model that presented in the above. For illustration purpose, we assume that there are 10 damaged blocks, 5 workgroups, at the upper level, and 3 affected areas as well as 2 distribution centers and 2 types of relief vehicle at the lower level. An exemplary chromosome for the genetic algorithm is illustrated in Figure 1. To be specific, *Substring 1* adopts nature number encoding and gens stand for damaged block index. *Substring 2* adopts integer encoding and gens stand for workgroup index. And *Substring 3* also adopts nature number encoding which from 1 to $|N_s| \cdot |N_d| \cdot |V|$.

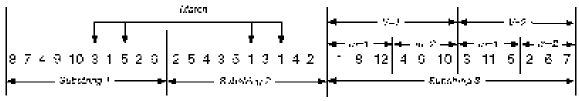

Fig. 1. Genetic algorithm encoding schema

In Figure 1, the *damaged blocks 3* and *5* in *Substring 1* match with *workgroup 1* in *Substring 2*, means that *damaged block 3* and *5* are repaired by *workgroup 1* and the sequence is determined by their time window LT_d (if $LT_3 \leq LT_5$, then the sequence is 3-5, else is 5-3). Other damaged blocks repaired sequence match with other workgroups in the same manner. The steps for decoding *Substring 3* shown as follows.

Step 1: Initialization $AD_n \leftarrow 0$, $SUS_{mnv} \leftarrow 0$, $SUV_{mnv} \leftarrow 0$, $w_{mnv} \leftarrow 0$, $AV_{nv} \leftarrow 0$, where AD_n denotes the amount of relief materials allocated to affected area n, and AV_{nv} denotes the amount of v style of relief vehicles allocated to affected area n, $TD = \sum E(\widetilde{D}_n)$ denotes the whole of n^*expected relief demand of all affected areas, $TS = \sum S_m$ denotes the whole of relief can supply by distribution centers;

Step 2: In order to ensure the satisfaction of allocating relief materials, we first allocate the largest proportion relief materials ($\lfloor TS/|N_d| \rfloor \cdot |N_d|$) by average $AD_n = \left\lfloor E(\widetilde{D}_n) \cdot TS/TD \right\rfloor$;

Step 3: Let $\widetilde{C}$ denotes the residual allocated relief materials set. Firstly, we find the minimal satisfaction of affected area by$n^* = \arg\min\{AD_n + 1 \big/ E(\widetilde{D}_n)\}$, where $\arg\min\{\cdot\}$ denotes the index of the minimal value, $n = 1, 2, \ldots, |N_d|$. Secondly, assign a relief material to the affected area, which means$AD_{n^*} = AD_{n^*} + 1$, and delete this item from the set of$\widetilde{C}$. If $\widetilde{C} \neq \phi$, then go to ***Step 3***, else go to ***Step 4***;

Step 4: We adopt the same method to allocate the emergency relief vehicle. First, allocate the emergency relief vehicles ($\lfloor NUM_v/|N_d| \rfloor \cdot |N_d|$) by $AV_{nv} = \lfloor D_n \cdot NUM_v/TD \rfloor$;

Step 5: Let $\widetilde{V}$ denotes the allocated relief vehicles. Then allocate $\widetilde{V}$ by the relative fairness. Firstly, we find the minimal satisfaction of affected area by$n' = \arg\min\{AV_{nv} + 1/\lceil D_n/Q_v \rceil\}$. Secondly, assign a relief vehicle ton', which means$AV_{n'v} = AV_{n'v} + 1$. Let$\left|\widetilde{V}\right| = \left|\widetilde{V}\right| - 1$. If $\widetilde{V} \neq \phi$, then go to ***Step 5***, else go to ***Step 6***;

Step 6: Mark$\lambda^* = \arg\max\{Substring3\{\lambda\} | \lambda = 1, 2, \ldots, |N_s| \cdot |N_d| \cdot |V|\}$, where $\arg\max\{\cdot\}$ denotes the index of the biggest value. If $\lambda^* = 0$ then go to ***Step 11***, else go to ***Step 7***;

Step 7: Compute v^*, m^* and n^*, by $v^* = \lceil \lambda^* / |N_s| \cdot |N_d| \rceil$,

$m^* = \lceil [\lambda^* - (v^* - 1) \cdot |N_s| \cdot |N_d|] / |N_d| \rceil$, $n^* = \lambda^* - (v^* - 1) \cdot |N_s| \cdot |N_d| - (m^* - 1) \cdot |N_d|$, let $w_{m^* n^* v^*} = 1$;

Step 8: $TS^*_{m^* n^*} = \min\{S_{m^*}, D_{n^*}\}$??update$S_{m^*} = S_{m^*} - TS^*_{m^* n^*}$, $D_{n^*} = D_{n^*} - TS^*_{m^* n^*}$;

Step 9: If $S_{m^*} = 0$, then let $Substring3((v - 1) \cdot |N_s| \cdot |N_d| + (m^* - 1) \cdot |N_d| + j) = 0$, where $v = 1, 2, \ldots, |V|$ and $j = 1, 2, \ldots, |N_d|$, else if $D_{n^*} = 0$ then let$Substring3(\lambda^*) = 0$ and$Substring3(n^* + (v - 1) \cdot |N_s| \cdot |N_d| + (m - 1) \cdot |N_d|) = 0$, where $v = 1, 2, \ldots, |V|$ and $m = 1, 2, \ldots, |N_s|$;

Step 10: Let $SUV_{m^* n^* v^*} = \min\{\lceil TS^*_{m^* n^*} / Q_{v^*} \rceil, AV_{nv^*}\}$, $AV_{nv^*} = AV_{nv^*} - AV_{n^* v^*}$, and if $SUV_{m^* n^* v^*} \neq 0$, then $SUS_{m^* n^* v^*} = \lceil D_{n^*} / (SUV_{m^* n^* v^*} \cdot Q_{v^*}) \rceil$, else $SUS_{m^* n^* v^*} = 0$, go to ***Step 6***;

Step 11: End and output AD_n, AV_{nv}, SUS_{mnv}, SUV_{mnv}, and w_{mnv}.

After decoding, we can obtain both the lower- and upper-level objectives. At the lower-level, we employ the relative fairness meta-heuristic to allocate relief materials and relief vehicles to the affected areas. Due to the path of delivering relief materials also followed the rules of traffic flow assignment. Therefore, the objective of the chromosome can replace by the objective of upper-level. However, due to the chromosomes are generated by random, if the completed repair time of damaged node later than the time window, the punishment value (PV) would be added to the objective of the chromosome to cut down the fitness of this chromosome and then take part in the selection and competition operation eventually. Additionally, in order to avoid the search space of stable genetic algorithm become narrow quickly and reach a local optimum, we adopt a sorting method (in descending order) for the fitness assignment. We use Pos to denote the sequence of individuals, $SP \in [1.0, 2.0]$ denotes the strength for selection, and $popsize$ denotes the population size, and then the fitness of the chromosome can be calculated by the formulation (20).

$$Fit(Pos) = (2 - SP) + \frac{2(SP - 1) \cdot (Pos - 1)}{popsize - 1} \tag{20}$$

In addition, the author adopts a crossover and mutation operation respectively for each substring to avoid generating an error code, for *Substring 1* and *Substring 3*, a two-point crossover operation and reversed transcription variation are taken and a single-point operation and interchange variation are taken for *Substring 2*.

4. Experimental Designs and Results

In the case of Northridge earthquake in America, there were many damaged blocks scattered throughout the post-earthquake road network. As the consequence, travel delays were sustained about weeks and months in the event of this earthquake. Moreover, the road network restoration problem for Sioux-Falls network under Northridge earthquake had been studied in [6], and the corresponding hazard map of the network had been studied by [12]. Where nodes 1, 2 and 3 denote the affected areas, and nodes 13, 20 and 21 denote the safe zones (civilians' destinations) with emergency shelters and/or medical facilities. The rest denote either business zones or residential zones (civilians' origins). The unbalanced trip generation and trip attraction patterns in business zones (i.e., nodes 9, 10 and 11) and residential zones (i.e., nodes 18 and 19) that are represented by asymmetric origin-destination matrices. For the original properties of the network, readers can refer to [12]. Therefore, the author employs Sioux-Falls road network under Northridge earthquake to demonstrate the validity and efficiency of the bi-level programming model and the proposed approach solution. Due to the limited by the length of this paper, the more information for this paper, you can visit the website http://lishuanglin.cn/publications/.

The proposed meta-heuristic has been programmed in MATLAB. the planning horizon $T = 72$h. The parameters of the genetic algorithm are tuned as follows: (a) the maximum iteration generation is 500 ($maxgen = 500$); (b) the population size is 50 ($popsize = 50$); (c) the crossover probability is 0.9 ($pc = 0.9$); (d) the mutation probability is 0.01 ($pm = 0.01$); (d) the punish value is $100h$ ($PV = 100h$). The average computation time after ten optimization runs is 883.65s. The experimental results are shown in Figure 2 (the emergency reliefs allocation, the required type of emergency relief vehicle, the number of emergency relief vehicles, and the required travel time from distribution centers (DCs) to affected areas (AAs) are list in the top right of each sub-graph). From Figure 2, we can see that the damaged block repaired and information updated, the emergency relief vehicle routes are changed and the required travel time become short. For example, on the first day, the emergency relief vehicle route from number *2* distribution center (node *20*) to number 2 affected area (node *2*) passes through *18-7-8-9-5-6*. After the damaged block *4* (link *19*) being repaired and information updated, the route from *20* to *2* is changed to pass through *18-16-8-6*.

5. Discussion and Conclusions

(1) In the post-earthquake emergency response phase, by restoring the road network, the time of relief logistics and civilian evacuation can be reduced. As seen from Figure 2, damaged blocks 4, 7 and 8 (links 19, 43 and 61) are repaired on the first day. After the network status information updating from 22:00 PM of the previous day to 6:00 AM of the next day, the vehicle routings are changed (i.e., from DCs 2 to AAs 2 at Day 2 and from DCs 3 to AAs 2 at Day 3). Therefore, after an earthquake, it is very important to restore the road network basic function immediately.

(2) Considering dynamic traffic flow for optimizing the road network repair sequence and relief logistics problem is more realistic. Because during the post-earthquake emergency response phase, the road network conditions are not very well, many civilians enter the road network. Therefore, the traffic flow in the road network will be increased substantially, and the travel time will be increased. As showed in Figure 2, the time window for damaged block 1 was violated. The main reason is the long travel time for sub-tours, and especially from Node 24 to Node 13 it almost took 6.79h (in normal times, it is only needed 0.88h).

(3) As showed in Figure 2, all the travel paths for relief logistics chose the edges of the network. The reasons for this phenomenon include: a) according to the dynamic traffic flow assignment, in the center of the transportation network, the traffic demand and traffic flow are very large, and the required travel time for the paths become longer; b) according to the road network characteristics (readers can refer to [12]), the road along the edges of the network are high-level road or highway. Though the distances is longer than others, the travel speed and road capacity are higher, then, the required travel time is shorter than others.

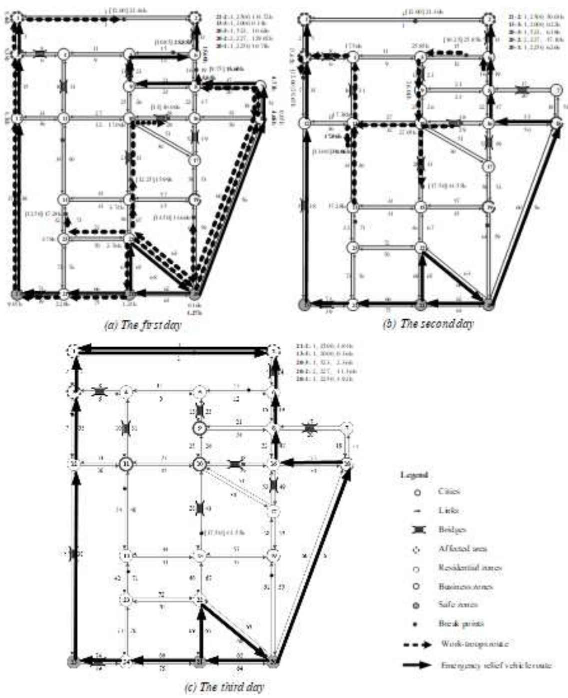

Fig. 2. (a) Road restoration and relief logistics result in the first day; (b) road restoration and relief logistics in the second day; (c) road restoration and relief logistics in the third day

In this paper, a bi-level programming model is proposed for relief logistics and road network repair in post-earthquake response. A meta-heuristic approach is proposed to solve the bi-level programming model. The experimental results demonstrate that the proposed to improve the relief logistics planning by considering the road network restoration. Further research will include: a) developing an online roll-horizon scheduling model that is capable of processing real-time data of road network status and vehicle routing; and b) extending the planning horizon and modifying the meta-heuristic to achieve dynamic decision making.

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