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The Combined Emergency Rescue and Evacuation Network Reconstruction Model for Natural Disasters with Lane-Based Repaired Constraints

Chung Yung Wang[1*] **and Ching Chuen Chang**[2]

[1,2]Department of Logistics Management, National Defense University, No. 70, Sec. 2, Central North Road, Taipei, Taiwan

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Abstract **—** Transportation difficulties associated with disaster relief are generally divided into evacuation problems and rescue problems. Despite the differences between these two types of difficulty, they both require the use of a common road network. Therefore, when examining the emergency reconstruction of damaged road networks, it is preferable to take the transportation requirements of both rescue and evacuation into account rather than examining each problem independently. The occurrence of natural disasters is often accompanied by large-scale damage to transportation networks and quickly restoring the basic functions of the transportation network system within the disaster zone is crucial to post-disaster relief efforts. The process of designing and reconstructing emergency networks requires a model capable of meeting the time constraints associated with evacuation and rescue, while minimizing travel costs. This study employed bi-level programming to construct a network reconstruction model, and imposed lane-based constraints to deal with the practical needs related to road repair. Mathematically, the model was a nonconvex mixed-integer nonlinear programming problem, for which we used simulated annealing in conjunction with the Lagrangian gradient projection method to solve the problem. This paper also discusses the operational procedures that provide the emergency network reconstruction model with high practicality and operability.

Keywords **—** rescue problems, evacuation problems, lane repair, bi-level programming, simulated annealing.

1. INTRODUCTION

When disaster strikes, the first and most important task is the rapid launch of disaster relief operations. Rescuing or evacuating people from the disaster zone in the least amount of time is critical to reducing the number of casualties and increasing relief efficiency. The successful functioning of all emergency systems depends on the normal operation of roads. Unfortunately, natural disasters often inflict severe damage on road networks; therefore, planning and performing emergency repairs to damaged road networks are essential to post-disaster relief operations. In the emergency reconstruction of road networks, the most important issue is the allocation of limited manpower and machinery.

Transportation difficulties associated with disaster relief are generally divided into evacuation problems and rescue problems. Evacuation problems involve the transportation of disaster victims from within the disaster zone to a secure location. Rescue problems involve the transportation of manpower and resources from outside the disaster zone to locations within the disaster zone. Relief workers attempt to identify the overall transportation requirements at the origins and destinations; however, consideration must be given to space impedance and regional factors in assigning the appropriate number of trips. Rescue problems are more complex than evacuation problems; however, they both use the same road network. Therefore, it is necessary to take the transportation requirements of both rescue and evacuation into account when examining the emergency reconstruction of damaged road networks. Furthermore, lane-based repair mechanisms are better suited to merging post-disaster network reconstruction models with practical problems. In this study, we improve the previous studies (Wang and He, 2003; Wang and Hu, 2005; Wang and Hu, 2007) and adopt the lane-repaired based decision variables in the network reconstruction model. Models that integrate the reconstruction of rescue and evacuation networks according to lane repair fit into the category of network design. Bi-level programming models are applicable to this kind of problem; however, solutions are difficult to derive, because of the nonconvex mixed-integer nonlinear programming that is required. This study performed analysis on the above issues, constructed a model, developed a solution method, and created a disaster scenario to explain the implications of our results. Conclusions and suggestions are also presented.

[*] Corresponding author's email: stellar@ms35.url.com.tw

2. LITERATURE REVIEW AND PROBLEM ANALYSIS

This study investigated the reconstruction of emergency networks in the least amount of time using limited resources. According to the Field Operations Guide (FOG) for Disaster Assessment and Response published by the Office of U.S. Foreign Disaster Assistance (OFDA, 1994), transportation-related planning and the status of logistical road networks are the primary factors influencing the implementation of disaster relief. The status of the emergency network, the repair planning of damaged lanes, the allocation of relief resources, and transportation assignments are all closely related to the overall effectiveness of operations. Network assessment is essential to post-disaster rescue and evacuation tasks. With limited human resources to perform repairs, rescue commander must make roadways a priority and deploy personnel to ensure clear access.

In Taiwan, plans related to highways for the prevention and mitigation of disasters are currently outlined by the Ministry of Transportation and Communications. The scope of the plans encompasses the road systems under the jurisdiction of the National Freeway Bureau and the Directorate General of Highways. The responsibility of repairing and reconstructing national freeways is delegated to engineering teams belonging to the northern, central, and southern region offices of the National Freeway Bureau. Maintenance offices under the Directorate General of Highways are in charge of restoring other highway network systems. The primary procedures for the repair and reconstruction include establishing an emergency response team, evaluating the situation, controlling traffic, surveying the disaster restricting access, investigating the extent of road damage, reopening and restoring the roads, conducting safety inspections, and restoring the roads to normal operations. The overall process is presented in Figure 1.

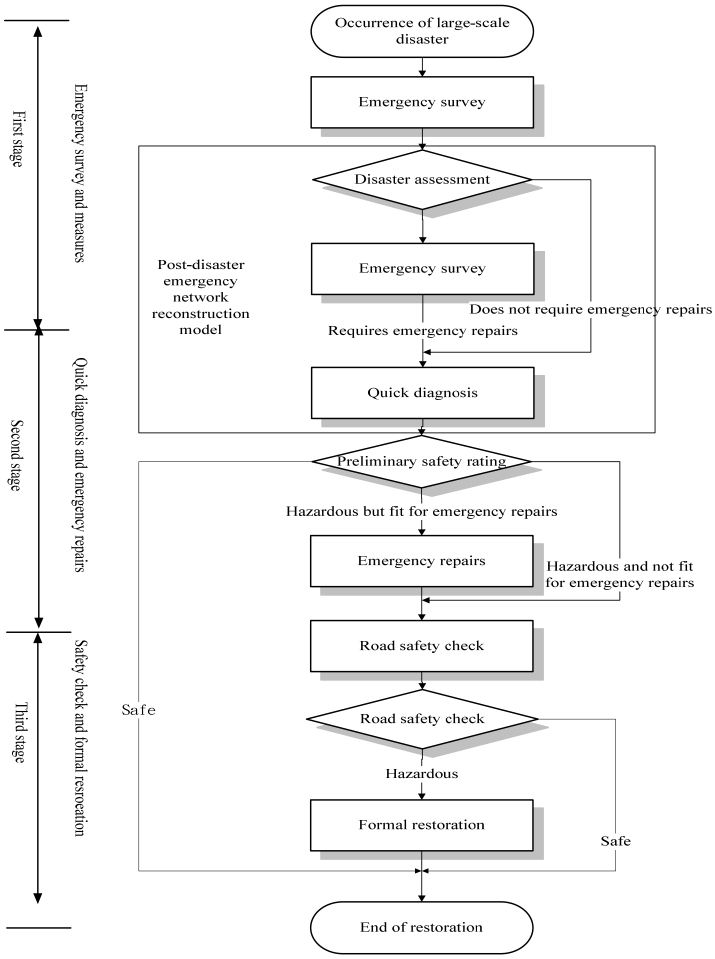

Figure 1. The emergency network reconstruction process (Lin *et al.*, 2002)

As shown in Figure 1, a quick diagnosis of damage to the road network and the proposal of emergency reconstruction strategies are meant to facilitate subsequent relief operations.

Comprehensive models for the emergency reconstruction of road networks must take into account the requirements of both rescue and evacuation. In the recent research, many studies of the literature usually focus on natural disaster emergency evacuation and rescue route planning, such as Tufekci (1995) developed a decision support system for hurricane emergency management. Pidd *et al.* (1996) provided a spatial decision support system, combined the geographic information system and simulation model to aid the emergency evacuation planning. Lovas (1997) emphasized the importance of emergency evacuations wayfinding. Fiedrich *et al.*(2000) developed a dynamic optimization emergency logistic model to optimize the emergency resource allocation after earthquake disasters. And they expect this model could minimize the total number of fatalities in the initial few days after strong earthquake. Cova and Johnson (2003) present a network flow model for identifying optimal lane-based evacuation routing plans in complex network. And their model could reduce the traffic delay at intersections in an evacuation plan after disaster. Feng and Wen (2005) provided traffic control strategies in earthquake areas and expected to guide the emergency vehicles and control disturbing traffic flows in and out the disaster areas. Another researches such like Sheffi *et al.* (1982), Han (1990), Shieh (1999), Huang (2001), Wang (2004), and Yi and Ozdamar (2007) have all focused on post-disaster or unique emergency situations. They subsequently categorized various phases of the operation, used computer models to simulate transportation and geological information systems, and hypothesized various transportation models to provide support for emergency evacuation decisions. But they all ignore that the transportation network destruction is uncertain and unpredictable after natural disaster. Each emergency evacuation and rescue planning must be affected by network reconstruction strategy.

Haghani and Oh (1996) noticed the important of network flow problems in disaster relief operations. They also formulated a multi-commodity, multi-modal network model and solution algorithms to analysis the problems. In their study, the transportation network may be damaged in the disaster had been noticed, but the network reconstruction did not be discussed. Chen and Tzeng (2000) developed a bi-level network reconstruction model. In this research, they focused on the optimal repaired order on each damaged point on a broken network post-quake and adopted a simulation approach to analysis the problem. Pourmohammadi (2008) focused on damaged bridges recovery for disaster relief services. In this paper, a mathematical model is developed to obtain the optimum number of bridge clusters and the repair sequence for these clusters. Orabi *et al.* (2009) developed a recovery planning model to support the optimization of post-disaster reconstruction work in damaged transportation networks. This model provides the capability of optimizing the recovery efforts in post-disaster situations in order to simultaneously minimize both the performance loss and reconstruction costs. The literatures of above are all focus on damage network recovery post disaster, but two important conditions are ignored in their models. First, the relief manpower demands are one of critical constraint damage network reconstruction after disaster. Because it is difficult to gather enough emergency network repaired manpower in a short period of time. Second, the victims evacuation and the rescuers rescue transportation behaviors dependent on the damage network reconstruction strategies, but the emergency transportation behaviors are also ignored in above models.

Wang and He (2003) pointed out that the network reconstruction problem is one of the most important problems in a large scale natural disaster. They employed a bi-level programming model for the design and reconstruction of road networks damaged by disaster. And the emergency network repaired manpower limited condition was also considered in the network reconstruction model. Under the assumption of fixed emergency transportation demands and a single type of transport, they employed the variational inequality (VI) sensitivity analysis method in conjunction with generalized inverse matrices using the gradient projection method in the design of a solution method to obtain Stackelberg equilibrium. This study analyzed the influence of post-disaster network reconstruction on the efficiency of emergency transportation from the perspective of the overall network under limited manpower. The resulting reconstruction model is applicable to the formulation of strategies for the repair of a large-scale road network system damaged. Wang and Huang (2004), Wang and Hu (2005), Wang and Yen (2006), Wang (2007), Wang and Hu (2007), Wang and Liao (2008), and Wang and Tsui (2012) conducted follow-up studies on emergency network reconstruction problems; however, two issues remain unresolved. First, these above models are theoretically acceptable; however they practicality is somewhat limited because estimated the repair required for damaged road sections according to the recovered ratio of damaged road capacities. But the recovered ratio is not suitable to operate in the empirical road repaired case. Therefore, to ensure the practical applicability in network reconstruction issues, it is necessary to revise the models mentioned above with a lane-based repair mechanism and merge the reconstruction model with practical problems. Second, previous models were based on either rescue needs or evacuation needs, and failed to consider the fact that they both require the same road network.

Network reconstruction using lane-based constraints constitutes a nonconvex mixed-integer nonlinear programming problem, which can be viewed as a type of combinatorial optimization problem. Heuristic methods are often adopted to derive near optimal solutions, among which simulated annealing has proven a simple and yet effective approach. Chardaire et al. (1996), Friesz et al. (1992), Lee and Yang (1993), Su et al. (2005), Gai and Pei (2005), and Gui (2006) used simulated annealing to solve nonconvex mixed-integer nonlinear programming problems and reported high computational efficiency. Thus, this study adopted simulated annealing to design a solution method for our model.

3. MODELING

In this study, the lane-repaired based decision variables are employed in the network reconstruction model and the previous studies (Wang and He, 2003; Wang and Hu, 2005; Wang and Hu, 2007) are improved. Models that integrate the reconstruction of rescue and evacuation networks according to lane repair fit into the category of network design. This study constructed a bi-level programming model, in which the upper level problem was the optimization of strategies for the reconstruction of damaged networks for rescue and evacuation purposes, and the lower level problem included the constraints for rescue and evacuation routing taking into account network reconstruction strategies. These two problems can be viewed as a leader-follower relationship, considering that different emergency network repair strategies lead to different victim routes choice behaviors for rescue and evacuation demands, which in turn influences the overall performance of network operations. The use of lanes as a unit of repair is vital to the process of fitting models to the operational requirements of network reconstruction. The transportation requirements of rescue and evacuation were analyzed as follows: (1) Evacuation problems involve the transportation of disaster victims from within the disaster zone to a secure location. The disaster victims' emergency evacuation travel choice behaviors include victims' evacuation route choice and destination choice behaviors. (2) Rescue problems involve the transportation of manpower and resources from outside the disaster zone to locations within the disaster zone. Relief workers attempt to identify the overall transportation requirements at the origins and destinations; however, consideration must be given to space impedance and regional factors in assigning the appropriate number of trips. Rescue problems are more complex than evacuation problems; however, they use the same road network. Therefore, it is necessary to take the transportation requirements of both rescue and evacuation into account when planning the emergency reconstruction of damaged road networks.

Based on the above considerations, the basic assumptions of the proposed model are as follows: (1) the relief headquarters possesses complete information on the road network, the cost function assumptions at various road sections are known, and the cost functions have not been calibrated according to sections of roads. (2) Rescue command can obtain complete, real time information on damage to the network surrounding the disaster zone. (3) The total emergency rescue transportation demands from each origin and the total emergency rescue transportation demands to each destination are known. The positions of rescue origin and destination are also known. (4) The total emergency evacuation transportation demands from each origin are known. The positions of evacuation origin and destination are also known. (5) The emergency transportation demands at the origin-destination pairs are homogeneous. Each disaster victim wishes to leave disaster area as soon as possible. The disaster commander understands victims' wish, too. Similarly, each disaster victim expects that he/she can be rescued within the shortest amount of time, and the rescue relief units also hold the same degree of expectation. (6) The road repair tasks are measured according to the number of lanes; rescue units have full knowledge regarding damage to the roads and the manpower required for road repairs.

The combined emergency rescue and evacuation network reconstruction bi-level programming model for natural disasters with lane-based repaired constraints is formulated as follows:

$$\min \ z\left(\mathbf{f},\mathbf{y}\right)=\sum_{a} f_a c_a\left(f_a,y_a\right),\forall a \tag{1}$$

St.

$$y_a=\underline{y}_a+\overline{y}_a\le y_a^{\max},\forall y_a,\underline{y}_a,\overline{y}_a,y_a^{\max}\in INT \tag{2}$$

$$\underline{y}_a\ge 0,\overline{y}_a\ge 0,\forall \underline{y}_a,\overline{y}_a \tag{3}$$

$$CAP_a=y_a\cdot CAP_{aL} \tag{4}$$

$$\sum_a \overline{y}_a K_{aL}\le \Gamma,\forall a\in m \tag{5}$$

$$\sum_{p\in\left(r,s\right)}\prod_{a\in p}\left(y_a\cdot\hat{\delta}_{ap}^{rs}\right)>0 \tag{6}$$

The rescue and evacuation location choice and route choice constraint is shown as follows:

$$\mathbf{c}\left(\mathbf{f}^*,\mathbf{y}\right)^T\left(\mathbf{f}-\mathbf{f}^*\right)-\mathbf{H}^{-1}\left(\mathbf{q}_E{}^*,\mathbf{y}\right)^T\left(\mathbf{q}_E-\mathbf{q}_E{}^*\right)-\mathbf{H}^{-1}\left(\mathbf{q}_R{}^*,\mathbf{y}\right)^T\left(\mathbf{q}_R-\mathbf{q}_R{}^*\right)\ge 0,\forall \mathbf{f},\mathbf{q}_E,\mathbf{q}_R\in\mathbf{\Omega}_{\mathbf{y}} \tag{7}$$

The above model is the proposed bi-level programming model. Eq. (1) presents the objective function of the upper level model, representing the minimized costs for network reconstruction. The decision variable y_a denotes the number of damaged lanes to be repaired. It also means that the capacity of each destroyed road to be recovered degree. The decision variable f_a represents the flows on link a. f_a is also representing the decision variable of the lower-level victim rescue and evacuation location choice and route choice combined model. Different network structure or link capacities will induce different evacuation and rescue destination choice and route choice behaviors in a network. When the vector of the upper-level decision variables $\mathbf{y}$ is changed, the vector of the lower-level decision variables $\mathbf{f}$ will follow to change. We cannot exactly express this relationship as a complete functional form between $\mathbf{y}$ and $\mathbf{f}$. The variables y_a and f_a are implicit function and can be expressed as $\mathbf{f}\left(\mathbf{y}\right)$. Eq. (2) dictates the number of usable lanes in road section a after repairs (y_a), which equals the number of usable lanes after the road was damaged plus the number of damaged lanes that were repaired ($y_a=\underline{y}_a+\overline{y}_a$), must be less than or equal to the maximum number of lanes, $y_a^{\max}$ (y_a, $\underline{y}_a$, $\overline{y}_a$, and $y_a^{\max}$ are all integers). That is, the maximum road recovery capacities are at most repaired to the original capacity. Eq. (3) indicates that the number of usable lanes after the road was damaged ($\underline{y}_a$) and the number of damaged lanes that were repaired ($\overline{y}_a$)

must be greater than or equal to 0. Eq. (4) defines the link capacity of road section a (CAP_a) as the product of y_a and the lane capacity of road section a (CAP_{aL}). Eq. (5) dictates that the amount of manpower required to repair each lane at road section a must be less than or equal to the maximum amount of repair manpower. Γ signifies the maximum amount of repair manpower that engineering units can invest in reconstruction, which we assume to be a constant; m denotes the set of all damaged road sections in the network. Eq. (6) ensures that at least one route connects every origin/destination (O/D) pair $\left(r,s\right)$ and satisfies the transportation requirements in between; $\hat{\delta}_{ap}^{rs}$ is an indicator variable equal to 1 when road section a is on path p and 0 otherwise. Eq. (7), the lower level model, is a victim emergency rescue and evacuation route choice and location choice combined model based on variational inequality problem (VIP), where Ω_y denotes the feasible region within the following constraints:

Flow conservation constraint:

$$\sum_p h_p^{rs} = q_E^{rs} + q_R^{rs}, \forall r,s \tag{8}$$

Non-negativity constraint for flow:

$$h_p^{rs} \geq 0, \forall r,s,p \tag{9}$$

$$f_a \geq 0, \forall a \tag{10}$$

Definition constraint:

$$f_a = \sum_{rs}\sum_p h_p^{rs}\bar{\delta}_{ap}^{rs} \geq 0, \forall a \tag{11}$$

$$\bar{\delta}_{ap}^{rs} = \left\{0,1\right\}, \forall r,s,a,p \tag{12}$$

Total trip generation constraint for evacuation:

$$\sum_s q_E^{rs} = \bar{O}_E^r, \forall r \tag{13}$$

Total trip generation constraint for rescue:

$$\sum_s q_R^{rs} = \bar{O}_R^r, \forall r \tag{14}$$

Total trip attraction constraint for rescue:

$$\sum_r q_R^{rs} = \bar{D}_R^s, \forall s \tag{15}$$

Non-negativity constraints for demands:

$$q_E^{rs} \geq 0, \forall r,s \tag{16}$$

$$q_R^{rs} \geq 0, \forall r,s \tag{17}$$

The first item of the VIP in Eq. (7) denotes the route choice behavior in each rescue and evacuation O/D pair $\left(r,s\right)$. The matrix of $\mathbf{c}\left(\mathbf{f},\mathbf{y}\right)$ is denoted the links cost function of the network. The second item of Eq. (7) expresses the evacuation destination choice behaviors for victims, and the rescue O/D pairs choice behaviors for rescuers are represented in the last item of Eq. (7). The matrix of $\mathbf{H}^{-1}\left(\bullet\right)$ is denoted the inverse demand function of each evacuation destination and rescue origin and destination. Analysis the lower-level problem of Eq. (7), under the monotonic assumption of the continuous functions $c\left(f\ ,y\right)$, $-H^{-1}\left(q_E^{rs},y\right)$ and $-H^{-1}\left(q_R^{rs},y\right)$, the sub-problem of the VIP in Eq. (7) can be expressed as an optimal nonlinear mathematical programming problem as follows:

$$\min\ z\left(\mathbf{f},\mathbf{q}_E,\mathbf{q}_R\right) = \sum_a \int_0^{f_a} c_a\left(\omega\right)d\omega - \sum_{rs}\int_0^{q_E^{rs}} H^{rs^{-1}}\left(\omega\right)d\omega - \sum_{rs}\int_0^{q_R^{rs}} H^{rs^{-1}}\left(\omega\right)d\omega \tag{18}$$

St. Eq. (8)-Eq. (17)

The Eq. (18) is a combined victim emergency rescue and evacuation route choice and location choice nonlinear programming model. The objective function of the Eq. (18) does not have any intuitive economic or behavioral interpretation. But the results of route choice behaviors and O/D choice behaviors for victims and rescuers can be expressed in the optimal conditions of the Eq. (18). The first order conditions for Eq. (18) as follows:

$$h_p^{rs}\left(c_p^{rs} - \pi^{rs}\right) = 0, \forall r,s,p \tag{19}$$

$$c_p^{rs} - \pi^{rs} \geq 0, \forall r,s,p \tag{20}$$

$$h_p^{rs} \geq 0, \forall r,s,p \tag{21}$$

$$q_E^{rs}\left[\left(\pi^{rs} - H^{rs^{-1}}\left(q_E^{rs}\right)\right) - u_E^s\right] = 0, \forall r, s \tag{22}$$

$$\left(\pi^{rs} - H^{rs^{-1}}\left(q_E^{rs}\right)\right) - u_E^s = 0, \forall r, s \tag{23}$$

$$q_E^{rs} \geq 0, \forall r, s \tag{24}$$

$$q_R^{rs}\left[\left(\pi^{rs} - H^{rs^{-1}}\left(q_R^{rs}\right)\right) - u_R^r - u_R^s\right] = 0, \forall r, s \tag{25}$$

$$\left(\pi^{rs} - H^{rs^{-1}}\left(q_R^{rs}\right)\right) - u_R^r - u_R^s = 0, \forall r, s \tag{26}$$

$$q_R^{rs} \geq 0, \forall r, s \tag{27}$$

Eqs. (19)~(21) represent the complementary slackness relationships in evacuation and rescue transportation route choice behaviors for victims, which means that the travel times of the paths being assigned evacuation/rescue traffic flows for a given O-D pair are equal to the minimum path travel times, otherwise path travel times between each evacuation/rescue OD pair are greater than or equal to the minimum path travel times. Eqs. (22)~(24) explain the complementary slackness relationship between the location choice costs comprising evacuation travel costs and negative inverse demand functions, and the evacuation transportation demands in O/D pairs. In other words, when the evacuation transportation demands q_E^{rs} from origin r choice the evacuation destination s, the location choice cost for victims in the O/D pair $\left(r, s\right)$ should equal to the minimum location choice cost u_E^s; otherwise, q_E^{rs} is equal to 0. Eqs. (25)~(27) explain the complementary slackness relationship between the location choice costs comprising rescue travel costs and negative inverse demand functions, and the rescue transportation demands in O/D pairs (r,s). In other words, when the rescue transportation need q_R^{rs} choice this O/D pair (r,s), the location choice cost between O/D pair (r,s) is equal to the minimum location choice cost $u_R^r + u_R^s$; otherwise, q_R^{rs} is equal to 0. In the event of large-scale natural disasters, all victims within the disaster zone wish to be evacuated to secure locations in the shortest possible time. And the rescue personnel within the rescue origin also wish to disaster zones as soon as. Impedance along the roads, suitable rescue OD pair matching and evacuation destination choice are all crucial factors influencing rescue and evacuation transportation decision. According to the optimized conditions derived from the above model, the expected behavior of rescue units and victims are the same. That is, the combined emergency rescue and evacuation network reconstruction model can be computed appropriate network reconstruction plan when occur a large scale natural disaster. Finally, by developing appropriate computing algorithms, one can solve the problem and obtain realistic network reconstruction strategies, and other crucial victim evacuation/rescue information for disastrous management purposes.

4. SOLUTION ALGORITHM

4.1 Establishing a super network

Owing to the behaviors of evacuation destination choice, rescue OD pair choice and evacuation/rescue route choice are all considered in the lower-level problem such as Eqs. (7), we can adopt the super network concept (see Figure 1) to transfer the lower-level problem into a standard fixed demand victims' evacuation/rescue route choice model. This approach can simplify the lower-level problem of the evacuation/rescue network reconstruction model.

The so call super network is that adds dummy links and nodes to the basic network. The negative inverse demand functions for evacuation and rescue demands with respect to the corresponding dummy links. Through the super network technique, the doubly constrained evacuation and rescue location choice and route choice problem can be transformed as a fixed demand equilibrium route choice problem. The only difficult aspect of solving this problem lies in the total trip generation and attraction constraint for rescue in Eqs. (14) and (15). Thus, the solution method must consider link capacity constraints in the dummy links which link between rescue super origin and rescue origins, and rescue destinations and super rescue destination. Take Figure 2 as an example. We respectively added a dummy super rescue origin (Node 9) and a dummy super rescue destination (Node 10) for the rescue origins (Nodes 1, 3, and 4) and the rescue destinations (Nodes 5 and 6). The demands from super rescue origin to super rescue destination are equal to total of all demands departure from rescue origins, and are also equal to sum of all demands arrive to rescue destinations. Each dummy link capacity constraint which connects from super rescue origin to the specific rescue origin is set as the departure demands of the rescue origin. As the same, each dummy link capacity constraint which connects from the specific rescue destinations to super rescue destination is set as the arrival demands of the rescue destination. As for evacuation, we added dummy evacuation destinations (Nodes 7 and 8) for each of the evacuation destinations (Nodes 1 and 2). Dummy links connect the evacuation destinations to the dummy evacuation destinations. Figure 3 outlines the super network constructed based on the content above. For the solution of emergency route selection problems with link capacity constraints, please refer to the Lagrangian gradient projection method developed by Wang (2001).

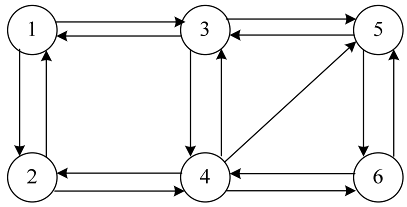

Figure 2. Basic Network

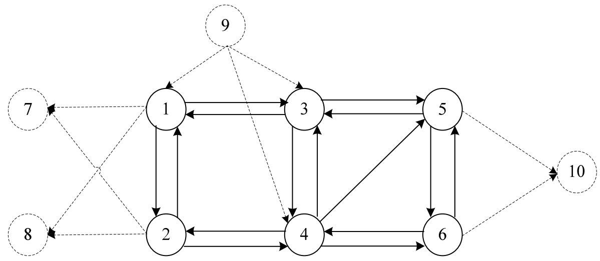

Figure 3. Super Network

4.2 The Solution algorithm

This study adopted a simulated annealing approach incorporated with the Lagrangian gradient projection method to reduce the difficult in dealing with the bi-level programming model. The solution process is as follows.

Step 0: Set the reduce temperature criteria n, the final temperature T, $l = 0$, $j = 0$, $i = 0$.

Step 1: Suppose the initial "temperature is" $T_j = 1000$, and the temperature adjustment coefficient α. Determine the initial reconstruction network, and employ the Lagrangian gradient projection method to solve constraints related to the selection of rescue routes, evacuation routes, and locations under Eq. (7), to derive the emergency transportation behavior in this network reconstruction strategy. Then, calculate the objective value of the initial reconstruction network, Z^n.

Step 2: Searching a better solution from the feasible solution set. Set $i = i + 1$, randomly generate a network reconstruction strategy $\mathbf{y}_i$. Use the Lagrangian gradient projection method to derive the solution and calculate the objective value of this network reconstruction strategy, Z_i^{n+1}.

Step 3: Compare the new objective value Z_i^{n+1} with the original objective value Z^n.If $Z_i^{n+1} < Z^n$, then set Z_i^{n+1} to be one of the new objective value, set $l = l + 1$. If $Z_i^{n+1} > Z^n$, then calculate $\mathrm{EXP}(\text{-}\Delta\mathrm{E}/\mathrm{T}_0)$, where T_0 is the current temperature, $\Delta\mathrm{E} = Z_i^{n+1} - Z^n$; if this value is greater than a value which randomly generate between 0 and 1, then also let Z_i^{n+1} be one of the new objective value and set $l = l + 1$.

Step 4: Temperature convergence check, if $l < n$ go to step 2, else if $l = n$, it represents the reduce temperature criteria has been reached, commence the cooling process and adjust the temperature to $T_{j+1} = \alpha \cdot T_j$. Replace the previous temperature T_j with the new temperature T_{j+1} and set $j = j + 1$, $j = 0$, $i = 0$.

Step 5: Check whether the temperature has been reduced to the setting final temperature T. If so, then stop the calculations; otherwise, return to Step 2.

For details regarding the Lagrangian gradient projection method in Step 2, please refer to Wang (2001) or Wang and Yen (2006).

4.3 Operation procedures and network adjustment

This study focused on the development of an emergency rescue and evacuation network reconstruction model based on lane repair for large-scale natural disasters. The model enables public works departments to determine which lanes of road require repair priority during the quick diagnosis and emergency repairs stage. The objective is to minimize network system total transportation costs and derive effective network reconstruction strategies, while selecting routes capable of satisfying the transportation requirements of both rescue and evacuation. The planning process is as follows:

Step 1: In the event of a disaster, immediately establish an emergency response team, have public works departments survey the damage, and compile detailed information related to the damage.

Step 2: Assess the emergency measures required.

Step 3: Assess the amount of manpower and equipment available for emergency measures.

Step 4: With the number of lanes as the unit, differentiate the damaged areas from the undamaged areas (in distance), add new nodes and nodal lines before and after the damaged areas in the original network, and revise the network into a pre-reconstruction network.

Step 5: Combine damage assessment information with manpower schemes, and apply the proposed model to the pre-reconstruction network to identify the road sections and lanes requiring emergency repair. Deploy repair personnel and equipment according to the optimal repair strategies.

Step 6: Perform emergency network reconstruction.

In Step 4, road sections were divided into damaged areas and undamaged areas according to the number of lanes to form a pre-reconstruction network. This is because only certain sections of the road may be damaged. Thus, the original road network must be revised to a pre-reconstruction network to meet the needs of emergency road reconstruction. The method of revision involves adding new nodes and nodal lines before and after the damaged areas in the original network, as shown in Figure 4. The new nodes and nodal lines must be noted in the adjusted network, and the associated information must be revised. The proposed network reconstruction model and solution method can then be employed to obtain optimal strategies for emergency repairs in a road network for rescue and evacuation.

Figure 4. The example of link adjustment

5. NUMERICAL EXAMPLE

In this section, the test network in Figure 5(A), comprising freeways, expressways, and highways between Keelung and Hsinchu, Taiwan, is used to verify the accuracy of the emergency rescue and evacuation network reconstruction model and solution algorithm developed in this study. The travel cost functions and the inverse demand functions for rescue and evacuation between locations in Figure 5(A) are shown in Eqs. (28) and (29), where γ is the location selection parameter and is set as 1.

$$c_a(f_a) = c_a\left[1 + 0.15\left(\frac{f_a}{CAP_a}\right)^4\right], \forall a \tag{28}$$

$$-\frac{\ln(q_R^{rs}) + 1}{\gamma}, \quad -\frac{\ln(q_E^{rs}) + 1}{\gamma} \tag{29}$$

The test scenario hypothesizes the occurrence of a large-scale natural disaster in northern Taiwan, where the road network has undergone varying degrees of damage. Authorities immediately form a disaster response center to coordinate command and contingency measures. Based on the Civil Defense Mobilization Reserve Act promulgated and implemented by the president on November 14, 2001, the Ministry of National Defense dispatches units to corresponding emergency command centers at all levels and delegates the task of performing emergency network reconstruction in northern areas to the Army Engineer Corps in coordination with relief units at various levels. After the first emergency survey, the command center obtains a list of major damage to highways complied by the Directorate General of Highways, Ministry of Transportation and Communications (Table 1). A total of 48 lanes in 22 sections of road have been damaged, severely affecting the transportation system. The original network was revised and divided into damaged areas (in distance) and undamaged areas. New nodes and nodal lines were added to the original network before and after the damaged areas, thereby establishing the pre-reconstruction network in Figure 5(B). At the same time, we hypothesized that the disaster victims would assemble at Tiding (4) and Muzha (24) to await evacuation. The total transportation capacity for evacuation is presented in Table 2. Considering the space impedance of roads and OD choice, we planned to have the victims evacuated to the Hsinchu Hospital in Hsinchu (20) and the 804 Armed Forces General Hospital in Guansi (33). Rescue units gathered at Hukou (18), Longtan (32), and Guanyin (40) in preparation for the rescue tasks at Tiding (4) and Muzha (24). The Armed Forces coordinated according to rescue requirements. The statistics regarding the rescue capacities of the origins and destinations are listed in Table 3.

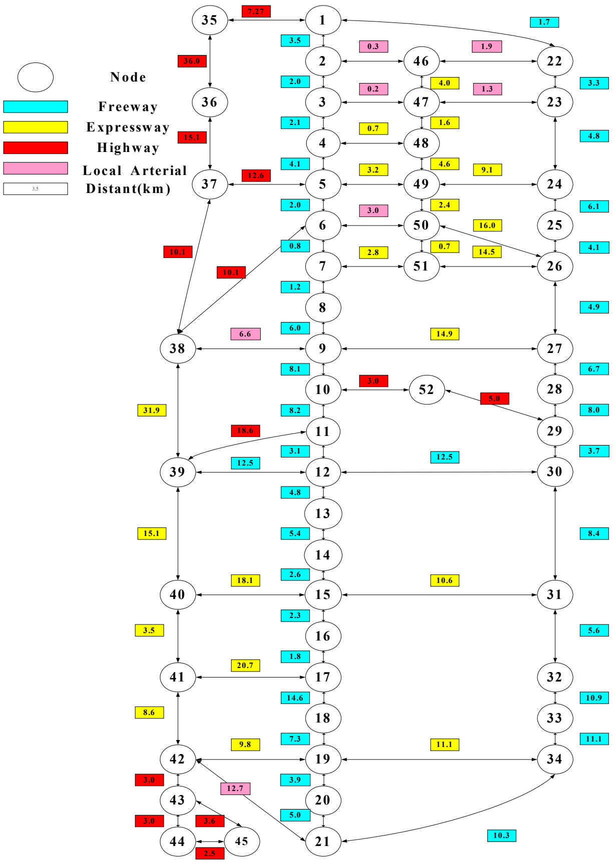

Figure 5(A). The test network

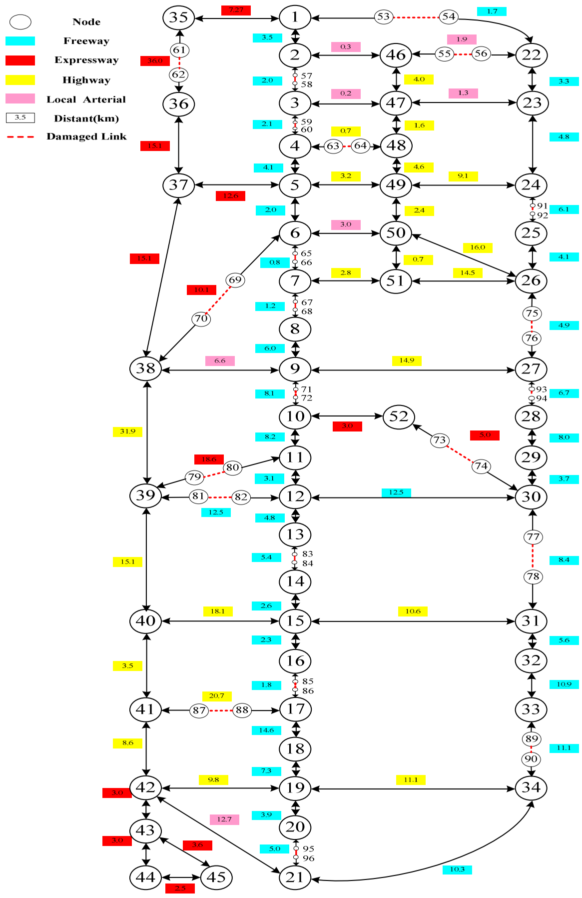

Figure 5(B). The pre-reconstruction network

Table 1. List of major damage to public roads provided by the Directorate General of Highways, Ministry of Transportation and Communications

Item	Damaged road section	Emergency repair measures	Damage condition	Number of lanes damaged
1	Xizhi interchange -New provincial highway No. 5 section	Awaiting emergency repair	Hollowing and loss of road foundation for approximately 1000m, road impassable	2
2	Donghu-Neihu section	Awaiting emergency repair	Blockage from landslide, affected area approximately 1200m long and 9m wide	1
3	Neihu-Tiding section	Awaiting emergency repair	Crocodile cracking in road surface for 1km, subsidence for 143m, estimated length for emergency repair: 1km	2
4	Dawulun-Kanding section	Awaiting emergency repair	Large gap in road foundation, affected area approximately 900m long and 10m wide	3
5	Tiding-Songshan section	Awaiting emergency repair	Blockage from landslide, affected area approximately 700m long and 23m wide	3
6	New provincial highway No. 5-Huandong Expressway	Awaiting emergency repair	Crocodile cracking in road surface for 540m, subsidence for 322m, estimated length for emergency repair: 600m	3
7	Yenping North Road-Huanhe North Road	Awaiting emergency repair	Crocodile cracking in road surface for 288m, subsidence for 143m, estimated length for emergency repair: 300m	1
8	Huanhe North Road-Sanchong section	Awaiting emergency repair	Hollowing and loss of road foundation for approximately 860m, road impassable	2
9	Muzha-Xindian section	Awaiting emergency repair	Hollowing and loss of road foundation for approximately 700m, road impassable	3
10	Ankeng-Zhonghe section	Awaiting emergency repair	Hollowing and loss of road foundation for approximately 1km, road impassable	1
11	Zhonghe-Tucheng section	Awaiting emergency repair	Hollowing and loss of road foundation for approximately 2km, road impassable	1
12	Taipei-Bali section	Awaiting emergency repair	Crocodile cracking in road surface for 798m, subsidence for 349m, estimated length for emergency repair: 900m	2
13	Wugu-Linkou section	Awaiting emergency repair	Blockage from landslide, affected area approximately 800m long	3
14	Taishan-Sanying section	Awaiting emergency repair	Blockage from landslide, affected area approximately 600m long	2
15	Yingge system-Dashi section	Awaiting emergency repair	Hollowing and loss of road foundation for approximately 890m, road impassable	2
16	Taoyuan-Dayuan section	Awaiting emergency repair	Hollowing and loss of road foundation for approximately 980m, road impassable	3
17	Dayuan-Aiport system section	Awaiting emergency repair	Blockage from landslide, affected area approximately 700m long and 80m wide	1
18	Neili-Jungli section	Awaiting emergency repair	Hollowing and loss of road foundation for approximately 500m, road impassable	3
19	Yushih-Yangmei section	Awaiting emergency repair	Hollowing and loss of road foundation for approximately 800m, road impassable	3
20	Yangmei-Sinwu section	Awaiting emergency repair	Landslide in side slope, road impassable for approximately 600m	3
21	Guansi-Chulin section	Awaiting emergency repair	Blockage from landslide, affected area approximately 700m long	1
22	Hsinchu-Hsinchu system section	Awaiting emergency repair	Blockage from landslide, affected area approximately 800m long and 50m wide	3

Table 2. The total trips generation from evacuation origin

Origin node	Demands	Origin node	Demands
4	3000.00	24	4000.00

Table 3. The total trips generation from rescue origin and trips attractions to rescue destination

O/D pairs	Origin			Destination	
	18	33	40	4	24
Demands	1500.00	2400.00	2100.00	2000.00	4000.00

The estimated manpower required to repair the number of lanes and distances indicated in the emergency survey is shown in Table 4. The scope determined for repair is outlined in Fig. 5B. In coordination with the emergency rescue and evacuation network model developed in this study, we derived the optimal repair strategies by repairing the minimum number of lanes with the most effective use of manpower. This strategy could provide a reference for decision-making units in planning the most optimal routes for rescue and evacuation.

Table 4. The repair manpower evaluation for each lane of damaged link

Damaged link	53-54	56-55	57-58	59-60	62-61	63-64	65-66	67-68
No. of damaged lanes	2	3	1	2	3	3	1	2
Repair manpower demands for each damaged lane (person/hr)	30	30	20	30	30	30	20	20
Damaged link	70-69	71-72	74-73	75-76	78-77	80-79	81-82	84-83
No. of damaged lanes	2	3	2	1	2	3	1	3
Repair manpower demands for each damaged lane (person/hr)	20	60	40	20	40	50	10	30
Damaged link	85-86	88-87	89-90	91-92	93-94	95-96		
No. of damaged lanes	3	3	1	3	1	3		
Repair manpower demands for each damaged lane (person/hr)	30	30	10	50	10	30		

In this case study, we assumed that to repair all of the damaged lanes would require 1,550 individuals. According to Article 34 of the Disaster Prevention and Protection Act, in the event that municipal, city, or county governments and regulating authorities of central disaster prevention and protection operations are unable to cope with disaster management, they may apply for support from the National Armed Forces. In the event of major disasters, the Armed Forces should actively assist in disaster prevention and response. We therefore assumed that the Armed Forces would apply two engineer battalions (600 individuals) to the emergency repair of damaged roads. Based on the model operations and network adjustment procedures established in Section 4.3, we combined simulated annealing with the Lagrangian gradient projection method. The results are presented in Table 5.

Table 5. The results of solution algorithm

Measure	Output data
repair manpower up limit/total repair manpower demands	600/1550
repaired lanes/damaged lanes	21/48
The total system transportation costs after input 600 repaired manpower(1)	922066.94
The total system transportation costs after repair all of the damaged lanes(2)	912598.31
The total system transportation costs if never fixed any damaged lanes(3)	1193131.50
Network performance recovery rate ((3)-(2))/(3)-(1))*100%	96.62%

Table 6. The optimal repaired manpower deployment and line repaired strategy

Damaged Link	The link capacity after repaired	No. of Repaired Lanes	Repair Manpower	Damaged lanes/original lanes in each damaged road
53-54	2000	1	60	2/3
56-55	0	0	30	3/3
57-58	1000	0	10	1/2
59-60	0	0	30	2/2
62-61	0	0	30	3/3
63-64	0	0	30	3/3
65-66	2000	0	20	1/3
67-68	2000	1	40	2/3
70-69	1000	0	20	2/3
72-71	3000	3	60	3/3
74-73	2000	1	40	2/3
75-76	2000	0	20	1/3
78-77	2000	1	80	2/3
80-79	1000	1	0	3/3
81-82	3000	1	10	1/3
84-83	1000	1	30	3/3
85-86	3000	3	30	3/3
88-87	0	0	0	3/3
89-90	2000	0	0	1/3
91-92	2000	2	50	3/3
93-94	2000	1	10	1/3
95-96	0	0	0	3/3

Table 7. Rescue/Evacuation O/D Demands

Objective	Origin	Destination				Total Demands
		4	24	20	33	
Rescue	18	965.51	534.49	--	--	1500.00
	33	0	2400.000	--	--	2400.00
	40	1034.49	1065.51	--	--	2100.00
	Total	2000.000	4000.000	--	--	6000.00
Evacuation	4	--	--	2103.17	896.83	3000.00
	24	--	--	916.11	3083.89	4000.00
	Total	--	--	3019.28	3980.72	7000.00

Table 8. The route planning and travel cost for each evacuation/rescue OD pairs

Objective	OD Pairs	Routes	Flows	Route travel cost	Rescue/ Evacuation location choice cost	Total Travel Cost
Rescue Transportation	18→4	18→17→16→15→14→84→83→13→12→11→10→72→71→9→8→7→6→5→4	965.51	57.44	15.77	73.21
	18→24	18→17→16→15→14→84→83→13→12→11→10→72→71→9→8→7→6→5→4→3→47→23→24	448.47	52.27	20.94	
		18→17→16→15→14→84→83→13→12→30→29→28→27→26→25→24	86.20			
	33→24	33→32→31→78→77→30→29→28→27→26→25→24	2400.00	42.64	30.57	
	40→4	40→39→11→10→72→71→9→8→7→6→5→4	1034.49	40.48	32.73	
	40→24	40→39→11→10→72→71→9→8→7→6→5→4→3→47→23→24	1065.51	55.29	17.92	
Evacuation Transportation	4→20	4→5→6→65→66→7→67→68→8→9→10→11→12→13→14→15→16→85→86→17→18→19→20	2103.17	61.78	8.65	70.43
	4→33	4→5→6→65→66→7→67→68→8→9→10→52→29→30→31→32→33	896.83	62.63	7.80	
	24→20	24→23→47→3→4→5→6→65→66→7→67→68→8→9→10→11→12→13→14→15→16→85→86→17→18→19→20	60.85	68.32	7.82	76.14
		24→49→50→51→7→67→68→8→9→10→11→12→13→14→15→16→85→86→17→18→19→20	855.26			
	24→33	24→91→92→25→26→75→76→27→93→94→28→29→30→31→32→33	3083.89	67.11	9.03	

The test results in Table 5 show that without the reconstruction of the network, the total costs for rescue and evacuation totaled 1,193,131.50; after complete repairs to the network, the total cost of rescue and evacuation totaled 912,598.31. Using the proposed model, we derived an optimal network reconstruction strategy using 600 persons, resulting in a total cost of 922,066.94 and a network recovery rate of 96.62 %. It is worth noting, however, that the manpower required is only 38.7 % of the 1550 persons required to repair the network completely, demonstrating the potential advantages of this approach. The total computation time is 98.2 minutes. The proposed approach enables the formulation of network reconstruction strategies and identifies the amount of repair manpower required for each section of damaged road, as shown in Table 6. It also enables us to plan transportation for rescue and evacuation between origins and destinations, as shown in Table 7. In the Table 8, we have obtained the used paths, traffic loadings, path travel times, location choice cost and total travel cost between each rescue/evocation OD pairs. We can find that for the same rescue/evacuation OD pair, the path travel times of the used paths are essentially the same; for each evacuation origin, there are same total travel costs to all of evacuation destinations; for all rescue OD pair, the total travel cost are also the same, where the total travel costs include route travel costs and location choice costs. We can also be found consistent with the results of Table 8 to the optimality conditions in Eqs. (19)~(27) and verifies that our solution is correct.

Due to the proposed solution algorithm is a meta-heuristic method. For the same numerical example, it has different computational result and execution time in each test experience. As the same numerical example in this chapter, we tested ten times and summarized the results in Table 9. In the Table 9, the best objective value is 917915 and the worst one is 940865. The average objective value is 927249.2. The average network recovery rate is greater than 90% and the objective value of the proposed solution algorithm is very stability. The fastest computational time is 52.55 minutes and the slowest computational time is 132.47 minutes. The average computational time is 93.53 minutes. It is a large variance in the executable time. The solution algorithm should be increased the speed of problem solving in the future research.

Table 9. Summary of test experience for solution algorithm

Test No.	Objective value	Computational time (min.)
1	922066	98.2
2	924519	130.75
3	930390	132.47
4	917915	105.42
5	940865	72.78
6	934770	72.47
7	920879	55.07
8	926705	108.53
9	927075	107.02
10	927308	52.55
Average	927249.2	93.53

6. CONCLUSION

This study arrived at the following conclusions and suggestions:

1. The proposed model for post-disaster emergency network reconstruction considers the differences between rescue transportation and evacuation transportation. With a limited number of personnel to repair damaged roads, we incorporated practical lane-based repaired considerations and constructed a bi-level programming model for road network reconstruction. The derivations of the optimality conditions in the lower level model are shown that the strategy of the network reconstruction is under the constraints of victim evacuation and rescue personnel route choice and location choice behaviors.
2. We simplified the model using a super network by combining simulated annealing with the Lagrangian gradient projection method to develop a solution algorithm. We then tested the model with a numerical example and compared the results with the optimized conditions to verify the accuracy of the algorithm.
3. We also proposed model operation procedures and a method for network adjustment to increase the practicality and operability of the proposed system.
4. The solution algorithm proposed in this study enables users to formulate network reconstruction strategies, identify the manpower required to repair each section of damaged road, plan transportation for rescue and evacuation between the origins and destinations, and calculate the corresponding costs for various emergency transportation routes. The obtained information could be used to support decision making for rescue and evacuation after large-scale natural disasters.
5. This model can also be applied to military issues, such as providing a reference for network reconstruction in war simulations where the war zone is subject to large-scale missile attacks, thereby enhancing military training and combat readiness.
6. In this study, we assumed a single type of transportation for rescue and evacuation. To increase the practicality of this model, future studies should consider multiple types of transports to reflect post-disaster transportation problems. The model in this study formed a nonconvex mixed-integer nonlinear programming problem, which only the simulated annealing method is currently capable of solving. Future studies could apply other meta-heuristic methods to increase the speed of problem solving.

NOTATIONS

a : link number

CAP_a : the link capacity of road section a

CAP_{aL} : the lane capacity of road section a

c_p^{rs} : the p^{th} path's travel cost between O-D pair (r,s)

$\mathbf{c}(\mathbf{f},\mathbf{y})$: vector of link travel cost functions.

$c_a(f_a, y_a)$: travel cost of link a

$\bar{D}_R^s$: total rescue trip attraction to destination s.

$-H^{-1}(q_E^{rs}, y)$: inverse demand function of each evacuation destination s

$-H^{-1}(q_R^{rs}, y)$: inverse demand function of each rescue origin r and destination s

$\mathbf{f}$: vector of link traffic flow

f_a : traffic flow of link a

h_p^{rs} : the p^{th} path's flows between O-D pair (r,s)

K_{aL} : the amount of manpower required to repair of lane L at road section a
m : set of damaged links
n : the reduce temperature criteria
$\bar{O}_R^r$: total rescue trip generation from origin node r
$\bar{O}_E^r$: Total evacuation trip generation from origin node r
p : path number
q_E^{rs} : victims' evacuation demands between O-D pair (r,s)
q_R^{rs} : rescue demands between O-D pair (r,s)
r : origin node.
s :destination node.
T: final temperature
u_E^s : the minimum evacuation destination location choice cost
u_R^r : the minimum rescue origin location choice cost
u_R^s : the minimum rescue destination location choice cost
y : vector of damaged lanes to be repaired
y_a : the number of damaged lanes to be repaired of link a
$\underline{y}_a$: the number of usable lanes after the road was damaged of link a
$\bar{y}_a$: the number of damaged lanes that were repaired of link a .
$y_a^{\max}$: the maximum number of lanes of link a
z : objective function
α : the temperature adjustment coefficient
Γ : the maximum amount of repair manpower
$\hat{\delta}_{ap}^{rs}$: indicator variable; if link *a* is on path *p* between OD pair *rs*, $\hat{\delta}_{ap}^{rs}=1$; otherwise, $\hat{\delta}_{ap}^{rs}=0$.
$\bar{\delta}_{ap}^{rs}$: indicator variable; if link *a* is on path *p* between OD pair *rs*, $\bar{\delta}_{ap}^{rs}=1$; otherwise, $\bar{\delta}_{ap}^{rs}=0$.
Ω :feasible solution area
$*$: the optimal value

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