A New Hierarchical Facility Location Model and Genetic Algorithm for Humanitarian Relief

Tzong-Heng Chi, Hao Yang, Hsin-Min Hsiao
Aletheia University
No.32, Zhenli St., Danshui Dist.
New Taipei City, 251 Taiwan

***Abstract*- A responsive and effective humanitarian relief is needed when the disaster happens suddenly. However, there are many sophisticated reasons prevent the coordination with other relief organizations and then decrease the responsibility and efficiency of relief. Thus a hybrid facility location model with non-fixed levels, shortest-longest radiuses, limited capacities, least warehouses and hubs, and uneven hierarchies with new discount factor α and global λ reduction is developed. Better to support the humanitarian relief, higher the cost and more complex of the relief network will usually be. It implies the production and conservation of feasible solutions more difficult when genetic algorithms are applied. Therefore, we propose the loci swap and adaptive contest for multi-fitness functions to improve the genetic algorithm. The experimental results show the utility and practicability of the developed hierarchical network model and corresponding solution genetic algorithm.**

I. INTRODUCTION

By July 2011, tens of thousands of people remained housed in temporary shelters or evacuated their homes due to the Fukushima Daiichi nuclear disaster introduced by the Tōhoku earthquake and following tsunami on March 11. The lack of effective integration of humanitarian assistance might be the truth. Unlike the commercial supply chain, the disaster needs occur irregularly and suddenly and the locations cannot be known in advance. Despite both of humanitarian funding and the global aid workers has significantly increased, the needs of affected populations have gone up as well and this is the area the humanitarian relief system sill falls short [16]. The objective of disaster response in the humanitarian relief chain is to rapidly provide relief to affected areas, so to minimize human suffering and death. However, the relief chain management has been known the key to the success of disaster relief operations but without gaining too much attention of researchers [19][30]. Also, though the logistics is central to the relief activities, it did not actually get the proper planned in the strategies of aid sector [3]. Shortly, to management material flows in relief chains, the unpredictable emergencies, adequate stakes, and timely logistics constitute the uniqueness and challenge [5].

The configuration of relief network will significantly affect the operation cost of logistics. Akkihal solved a p-median problem based on the weight of mean annual homeless people because of the natural disasters [1]. Covering location models, often used in the location decision of emergency facilities, provide coverage to demand areas if they are within a predefined service distance [12]. Balcik et al. firstly developed a covering and then hub covering model for humanitarian relief [3]. The p-center model was used to provide the timely relief by [17]. The prepositioning of warehouses is financially prohibitive for most of relief organizations [4]. Alternatively, temporary supply-collected hubs are proposed to complement the warehouses. However, cooperation or coordination among relief organizations and donators can occur at any situation, or at any level. The hierarchical model, which has been useful and applied widely [27], is adopted to provide the needed flexibility. We thus integrate temporary storage and stockpiling warehouses based on the hierarchical combination of maximum and total distance facility location model to accommodate to the transient influx of donation and contribution coming from many sources.

The hub covering and p-center problem with variable values of p has been showed NP-hard [11][28]. In [28], heuristics was used to solve their proposed hierarchical hub maximal covering problems. A hybrid meta-heuristics of genetic algorithm (GA) with simulated annealing (SA) was developed and SA was applied in the production of initial population [22]. The hub covering problem is difficult, even finding feasible solutions is a challenge. They then solved the 3-level hierarchical hub maximal covering problem with determinate cover radiuses by CPLEX [28]. On the contrary, a Tabu based heuristics for the generalized hierarchical covering location problem was developed in [20]. A subgradient-based heuristic incorporating the Lagrangean-surrogate relaxation was used to solve a 2-level hierarchical hub maximal covering location problem. We herein develop a new GA for the new proposed hierarchical hybrid facility location model based on our previous work in the development of the small-world GA [6].

This paper is organized as follows. The humanitarian relief logistics and motivation will be reviewed and introduced first. We then explain our model. After the description of our GA solution method, it is followed by the experimental design and analyses. Finally, we conclude with some final remarks.

II. HUMENITARIAN RELIEF LOGISTICS

The primary objective of humanitarian aid is to save lives, alleviate suffering, and maintain human dignity. Ensuring the right things are provided at the right place at the right time is the way to meet the goal of the humanitarian relief. In every relief phase, the supplies and people are continuously required to be delivered faster and more effective as possible. To design the network for humanitarian relief, the p-median, p-center, and covering models are typical and common for the facility location problems [2][24]. The *p*-median problem asks selected *p* facilities to minimize the total (average) distances (or costs) for supplying customer demands. As the *p*-center problem, it is asked that selected *p* facilities can minimize the maximum distance between any customer and its nearest center. The location set covering problem locates the least number of centers to serve all customers. In another way, to consider the agglomeration of flows, the used hub location model seeks to find the best location for hubs and the assignment of non-hub nodes to hubs [29]. The objective in the design of the network includes the cost to establish hubs, the cost to transport people and supplies for every pair of spoke nodes, and the operating cost. This study is mainly based on the hub location model and mixed with non-fixed levels, shortest-longest radiuses, limited capacities, least warehouses and hubs, and uneven hierarchies.

Duran and et al. developed the emergency supply prepositioning based on the upfront investment, operation cost, and average response time for humanitarian relief organization CARE [9]. Fiedrich et al. then concentrated their effort on the initial period with the minimized number of facilities and find the optimal solution for resource allocation [14]. Though multi-criterion is common to the logistics network design, it will cause higher cost due to the complexity of humanitarian relief. Badly, the design of relief network usually taking more considerations is indeed an important issue [13]. However, once the budget is mainly concerned, *p*-center basis could be the candidate such as [17]. More reviews can be found in [3].

Two keys are considered here when designing the relief network: coordination and then responsibility. There are many reasons to hinder the response such as non-standardized needs assessment, local politics and language barriers, non-full authority, weak trust among organizations, and so on. Hence the coordination among governments, militaries, and NGOs is an important challenge and issue. On the other hand, except to contract with local stores or supermarkets such as Walmart [10], and cooperate with 2-, 3-, and 4-PL such as FedEx or DHL, the challenges met in the coordination of relief transportation also stem from the difficulties introduced by lumpy, uncertain demand and highly variable global shipping destinations. Unfortunately, shipper collaboration is not currently observed in the relief chain [4]. In [5], the system flexibility had been introduced and specifically stressed in this study. Though the idea of integration has been studied in [18][21][26][31], but there is no literature addressing the related network designing practices in the domain of humanitarian relief. Therefore, we took the hub model as our base. The hub can bring more flexibility and advantage like the reduction of safety stock, sharing of risk, the consolidation of shipment, and easiness to coordinate.

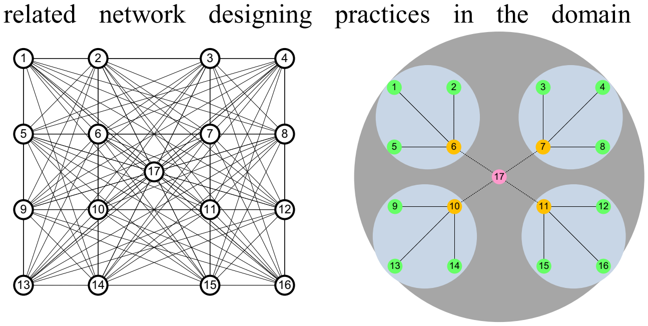

Fig. 1. (a) A 17-node complete graph with 136 edges. (b) A 2-level 17-node hub-and-spoke network with only 16 edges.

With reference to the unpredictable sources and volume of the humanitarian aids, the prepositioning of hubs without the permanent storage but only temperately collecting, storing, sorting and delivering aids, such as the cross-docking, seems suitable and necessary. Specifically to the transient influx of aids, hub locations filling the spatial and temporal requirements are indeed possible. The requirements can be the timely processing path from the contributors or donators to the hubs and to the demand destinations or having enough space to pile aids. Moreover, after the assessment in the beginning of the disaster, the collection and classification of relief supplies are needed to be faster to hasten the shipping operations to the right destinations as soon as possible. That is, the function decomposition is needed and usually with more spaces. The hub location model fills it and has the economies of scale comes from agglomeration. However, there is still a problem that having too many hubs in the same level. Therefore, by now, it is only used in the huge distribution center or special areas, e.g. forbidding terrain or road-damaging regions, with helicopter relief [3]. Our solution strategy is the uneven hierarchical model. In fact, the hierarchical model naturally occurs in the industrial context, schools, and health care sector such as from the lowest doctor's office, a small clinic, and to a highest full-service hospital [12][25][27]. Also the hierarchical tree tower formed in our model, i.e. trees of sub-trees, to be the points to coordinate with other relief organizations in each level such as cross-functional integration, common consolidation et al. [18][27]. We hence propose the hybrid facility location model with non-fixed levels, shortest-longest radiuses, limited capacities, least warehouses and hubs, and uneven hierarchies for the humanitarian relief network. Because of the trees formed by the hierarchical hubs, this model is expected to provide more flexibility to integrate with other networks to promote the coordination, and then hasten the response with lower cost.

III. Model And Solution Algorithm

None can tell at where the next disaster will be. Indisputably, disasters come irregularly and suddenly. So we give a guess first by a reference model, design a GA for it, and test it with historical disaster data. To coordinate many organizations with different purposes and missions, usually, it should be multi-objective. However, it cannot be known in advance. That is, the hybrid facility location model is our guess. Also, the objective of the reference model is only a main axis to be referred but not the whole story. Instead, other objectives and constraints are considered soft in this reference model. So called soft, the objectives or constraints are approached or violated as much or less as possible.

A. *The Mathematical Formulation*

Hubs are special nodes, usually are linkages, hinterlands, or hierarchies formed by spatial organization viewpoint, which

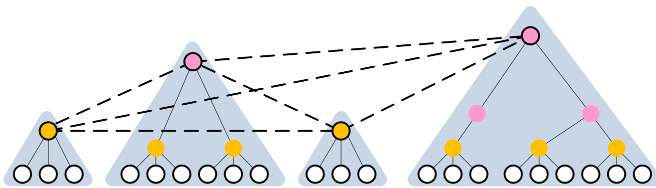

Fig. 2. It is a conceptual model where the lowest white nodes are demand sites, yellow nodes are 1-level warehouses, and all of upper pink nodes are hubs. The bordered treetop hubs with subtrees form a hub-and-spoke network.

are part of a network [23]. The agglomeration and scale economies are introduced by hubs which facilitate connectivity between interacting disaster areas, demand nodes, warehouses, and other hub sites. The number of edges between nodes is reduced dramatically as illustrated in Fig. 1 with only 2-level hierarchical tree tower. Three assumptions are made usually in the study of hub problems: the hub network is a complete graph, the flow economies of scale are represented by a single discount factor α to the inter-hub transportations, no direct service between spoke nodes [2].

To form the hierarchical configuration, the rising power, to against the down force of transportation cost with directly connected and shorter distance, comes from the discount factor to the transposition cost [23][15]. However, the hubs in this study, e.g. schools, parking lots, or cargo terminals, are usually not regular warehouses or even distribution centers. That is, the cost to install hubs is cheaper than warehouses and, moreover, inversely proportional to the number of hierarchies as addressed in [15]. By the literatures, the discount factor α is usually fixed. Instead, the reference [23] proposed the nonlinear cost function as shown in below where the cost is increasing at a decreasing rate as flows increase.

$$\Phi = \theta(\Sigma_a \Sigma_b F_{ab} X_{amnb} / \Sigma_a \Sigma_b F_{ab})^{\beta} \qquad (1)$$

The θ and β are adjustable parameters. For origin a and destination b, F_{ab} is the amount of flow between a and b and X_{amnb} means the proportion of flow from a to b that is routed via hubs m and n. It also implies the discount dependent to the whole network configuration. In this study, the network consists of warehouses and hubs located in different levels with asymmetric edges. Therefore, the discount is modified as shown in formula (2):

$$\alpha_{mn} = \theta(F_{mn} / \Sigma D)^{\beta} \qquad (2)$$

This link-dependent discount is similar to the formula (1) except it is applied to the link from lower warehouses or hubs to higher hubs, or the inter-hub between tops of trees. Noted here, links from demand nodes to warehouses are not included. Besides, the ΣD is the overall demands estimated by the census data in the designate area. Since the network will be separated into many distinguished tree towers based on the distribution of population, the scale of inter-tree flow is larger than flows from lower level hubs to higher ones. To reflect the economies of scale brought by the inter-tree links, another discount factor λ is introduced as shown in formula (3).

$$\lambda = 1 / (|E_I| - |E_K|) \qquad (3)$$

E means the edges and $|E|$ is the number of edges where $|E_K|$ represents the total pair-links between all of treetops and $|E_I|$ represents the number of edges for the complete graph constructed by all of warehouses. We call this λ reduction to reflect the global advantage brought by the hierarchical feature and force the treetops being closer with each other to form a more compact forest. Herein, it is not as the same as the airline network where the hub means the airport and costs much more. The open cost of a hub here is even cheaper than warehouses. In short, our reference model is shown in Fig. 2 having non-fixed levels, shortest-longest radiuses, limited capacities, least warehouses and hubs, and uneven hierarchies with new discount factor α and global λ reduction. It is as the following:

N	The set of all nodes.
I	The set of warehouses.
J	The set of hubs.
K	The set of hubs which are treetops and $K \subseteq J$.
W	Open cost for a warehouse.
H	Open cost for a hub.
F_{ab}	The flow from node a to b.
C_{ab}	The unit cost of transportation from node a to b.
D_{ab}	The distance from node a to b.
l, L	The l is the level of some node and $l \in Z^+$. L is the maximum value of l. If it is a demand node, its level is 0. If it is a warehouse, the level is 1. The $k(l)$ or k_l denote the node k is located at level l. Inversely, l_k or $l(k)$ means the level of k. For any set of nodes, e.g. N_l or $N(l)$ means the set of sites at level l. Also, The N_l is an empty set if $l < 0$ or $l > L$.
Q_l	The Q_l represents the capacity limitation for a warehouse or hub at level l.
$X_{mn(l)}$	$X_{mn(l)} = 1$ if a node m at level l-1 is assigned to a node n at level l. For the convenience, X_{mn} is used if the level is not concerned and without any confusion. Since there is no gap allowed between two levels, only the higher level is marked. Also, this assignment is asymmetric and the demand nodes are the only ones at the bottom level 0.
e_n	It represents the weighted longest distance of the demand site allocated to the warehouse or hub n.

$$Min \sum_{i\in I} WX_{ii} + \sum_{j\in J} HX_{jj} + \lambda\Big(\sum_{n\in I\cup J} e_n + \qquad (4)$$
$$\sum_{m\in J_{l(s)-1}} \sum_{s,t\in K} \sum_{n\in J_{l(t)-1}} F_{mn}(C_{ms}D_{ms}X_{ms} + \alpha_{st}C_{st}D_{st}X_{st} + C_{tn}D_{tn}X_{tn})\Big)$$

s.t.

$$\Sigma_{n\in N(l)} X_{mn(l)} = 1,\ \forall m \in N_{l-1} \qquad (5)$$

$$X_{nn} = 1,\ \forall n \in I \cup J \qquad (6)$$

$$\Sigma_{m\in N(x')} X_{mn(l)} = 0,\ \forall n \in N,\ \forall x' \in \{x \mid |l_x - l_n| > 1\} \qquad (7)$$

$$\Sigma_{m\in N(l-1)} F_{mn} X_{mn(l)} \leqq Q_l,\ \forall n \in N_l \qquad (8)$$

$$e_n \geqq D_{mn} X_{mn(l)},\ \forall m \in N_{l-1} \text{ and } \forall n \in N_l \tag{9}$$

$$X_{mn(l)} \in \{0, 1\} \tag{10}$$

The first and second items of the objective are the covering requirement to find the least warehouses and hubs to cover the whole demands. The third term asks for a minimax configuration because the shortest radius is concerned, i.e. it seeks the longest "radius" to be shortest for each warehouse and hub. As the final term, it is about a hub-and-spoke network. For the treetop hubs connected with each other fully, other hubs or warehouses in a tree on lower levels are spoke nodes to the treetop hub. Totally, the objective is to minimize the total open and transportation cost and to know the location of warehouses and hubs, and the allocation between nodes.

Actually, this is a successively inclusive model and single assignment, the lower nodes can be covered by higher nodes more than one time to induce the hierarchical form as shown in Fig. 1 (b), the node 6 is a top of sub-tree covering nodes 1, 2, and 5. The treetop, node 17, covers all of other nodes. Otherwise, the lower node can only be assigned to one higher node as noted by constraint (5), e.g. the nodes 6 can only be assigned to node 17. A warehouse or hub is chosen from some potential site and X_{nn}= 1 is specified in the constraint (6). Since level-skipping is not allowed, it is noted by (7). For a warehouse or hub, its capacity is limited, the summation of incoming flow cannot excess the capacity of it, and denoted by the constraint (8). The objective prefers the longest distance of transportation in each level to be shortest. The constraint (9) thus finds the longest one firstly and the objective minimizes it later. Finally, the $X_{mn(l)}$ is the only binary decision variables to indicate the locations of warehouses and hubs and allocations from demand nodes to warehouses and hubs to hubs. However, this is only a reference model because the happening probability of disasters is totally not predictable. The main idea here is that we give a guess and test it with the disaster simulation based on the historical disaster data.

B. The Genetic Algorithm

A GA is a general search heuristic that mimics the process of natural evolution. Because there are always too many constraints, the genetic algorithm cannot be effectively applied to logistic network design problems without any modification [7]. Also, since the mentioned model is only a reference mode and cannot guarantee the best performance once the disaster

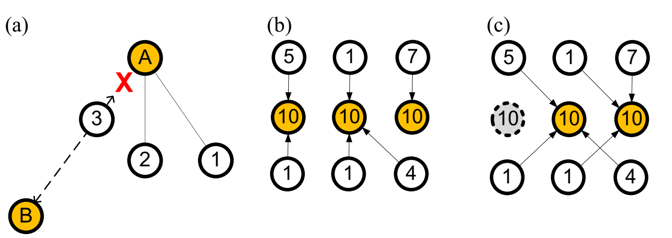

Fig. 3. The yellow and gray ones are chosen and disclaimed centers separately. The centers can be hubs or warehouses. (a) The node 3 is assigned to more distant center B but not closer center A. (b) The worse location-allocation network with 3 centers. (c) The better location-allocation network with only 2 open centers.

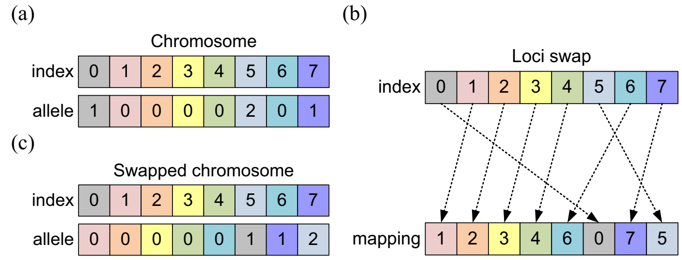

Fig. 4. (a) An original chromosome. (b) It is the mapping. For example, the gene 0 has been swapped to locus (index) 5. (c) The mapping result.

happened, it is not adequate if the cost function, usually used in GAs for facility location problems, is the only one consideration. The hierarchical facility location problem actually is a combination of location and allocation problems. Except the problem in the sequence of allocation will be explained later, geographical characteristics are also important considerations in the real life. To highlight the focus of this problem, we simplify the questions and only consider the mountain ranges of continent but not include the road, railway, airline, and ocean-route because of the essence of virtual assignment. However, it is applicable once the related information involved. In addition, there is one adaptive contest and two categories of operators to improve the GA: *FM* (Feasibility-checking-and-Modification) operators, and *LE* (genes' Loci Exchange) operator.

The fishnet phenomenon was discovered when many heuristics are applied to the design problem of logistic network because of many constraints [7]. It means a high ratio of infeasible solutions will be found in the execution of GAs. So modification and penalty are used but not passively let infeasible solutions discarded. There are four common causes to produce infeasible solutions in this study: the geographical barrier, hierarchical fault, redundant capacity, and deficiency of warehouse. We design four *FM* operators correspondingly. The FM_1 is used to modify the solution by making the minor reallocation to avoid the violation of geographical barriers. Since the GA randomly opens hubs in different levels, however, it is easy to find gaps between levels. For example, there is no hub between level 3 and level 6. The FM_2 corrects them by the reduction of higher level hubs and make hubs successive. The utilization of capacity is also one of the keys to optimize the network configuration. However, due to the randomness of GA, it will get penalty by the proportion of the idle capacity. The FM_3 is in charge of this job. By the randomness again, the capacity of warehouses may not be enough to support all demands. The FM_4 will check this situation and score it with enough high as a penalty.

For the capacitated problems, the sequence of allocation was usually neglected [7]. If so, a closer demand node might be assigned to a distant warehouse or hub. As shown in Fig. 3 (a), by the labeled sequence, the nodes are assigned to the center A one-by-one. Because that the capacity of center A is full, the node 3 is assigned to a more distant center B. It failed to get the optimal solution. Also, it is more cost-effective to change the network topology than adding facilities to improve the service level [21]. Given the vertical line distance as 1, the distance of sloping line is 1.414, and the hub cost is 10, we can find the total cost is 50.656 for Fig. 3 (b) and only 43.968 for Fig. 3 (c). The labels mean demands for white spoke nodes and capacities for yellow hubs.

Because that the sequence of assignment is implicitly encoded in the genes' loci of the chromosome when GAs re applied, therefore, we designed the *LE* operator to swap node "labeled number" as shown in Fig. 4. On the other hand, when to use this operator is also a key issue. Better effect is gained when the *LE* operator is used in the late convergence phase but not initial exploration phase in the execution of GAs. This operator allows the GA to reuse the same content of the chromosome and make the GA more efficiency.

As mentioned, better to support the humanitarian relief, higher the cost will be. It also can be a multi-objective form and an uneasy job to combine the objectives with different measurements by only assigning weights. The objective of hierarchical model is also closely related to multi-objective model [8]. Following our previous research results in [6], we designed four fitness functions and make them compete with each other in an adaptive contest instead. They are actual cost function f_1, nonlinear-weighted cost function f_2, minimax hop distance function f_3. For the shortest radius of center problem, the goal is to make the longest radius to the spoke node as shorter as possible. This requirement is also applied to the embedded hub-and-spoke network. That is, the total cost is not the only one concern here. Once donators or contributors are considered, how to make the relief aids can be faster and easier to reach the demand side should be important. Yet the real distance cannot tell the whole story especially about how the flow interacts with the network configuration. We thus consider the hops between hubs as an import index f_3 to point out the efficiency of relief network associated with the time to delivery aids. However, no matter the real or weighted cost function, and the hops between origins to demand sites are not really equal or interchangeable with each other. We view them as soft objectives and make them compete with each other but not combining them directly as what the multi-objective GA usually does. As f_2, it is based on the edge dependent local discount α and global λ reduction.

Finally, the disaster simulation is executed to examine the effect of the network. Because there are only the historical epicenters of earthquake, the disaster area are circled with the estimation based on the Richter magnitude scale. Once the disaster area has been identified, we can estimate the relief efficiency by calculating the transportation from origins to disaster areas which are sets of destination nodes. The calculation is easily approximated by a global transportation cost minus the local transportation cost in the disaster area. Strictly speaking, this is only an index f_4 but not really represents the complicated relief process. This is the last, i.e. the fourth, soft fitness function. The proposed humanitarian relief genetic algorithm (HRGA) is as shown in Fig. 5.

```
Generate the initial population P randomly.
repeat
    for each chromosome c in the population
        Calculate the fitness function f1, f2, f4, and f4.
    end for
    Selection(P) by the contest of f1, f2, f4, and f4.
    Crossover(P)
    Mutation(P)
    Modification(P) with FM1, FM2, FM3, FM4.
    if match the predestinate condition
        Execute LE operator
until Stop criteria
```

Fig. 5. The proposed HRGA algorithm for the humanitarian relief.

IV. Experimental Design

Without loss of generality, the experiments were based on the real data of Taiwan but with some assumed scenarios. We extracted the census and natural disaster data from public web sites and databases. In Taiwan, there are 368 cities, townships, and districts in city. The census data came from the Taiwan government notice and all of 345 regions in Taiwan's main island were chosen [33]. As the geographical data of latitude and longitude, they were represented by the local administrative offices and located by the Google map. There are 45 recorded earthquakes of Taiwan, happened from 1963 to 2010, stored in the National Geography Data Center [32]. That is, totally, 390 sites with varying levels of demands were used in each experiment.

The experiments were separated into three parts: one- or two-level, fixed multi-level and non-fixed hierarchical networks. In the first part, it includes terrain features, historical disaster data, and network models. Since there is a Central Mountain Range running from the north of the island to the south, the population is distributed around the Taiwan Island. It is not effective if the relief paths leap over high mountains. We also conducted two ways to assess the impact of an earthquake. The estimated demand is only imposed on one node and called spot demand. Or, it is called distributed demand model if the impact is distributed to around nodes with specific radius based on the actual Richter magnitude scale. The second part examined the effect of fixed multi-level hierarchical model usually used in [12][20][28] [28]. As the third part, the effect of locally edge dependent α discount and global λ reduction was examined first. Then, the cost, number of infeasible solutions, and simulation of disaster relief are shown to illustrate the effect of loci swap in the proposed HRGA. Finally, the experiment of adaptive contest with disaster simulation will be used to conclude the whole effect of our HRGA. All of experiments were repeated at least 25 times and usually the average of results was used.

V. Experimental Results And Analyses

We first examine the effect of p-center, p-medium and covering model related to the index f_4 of disaster relief. As shown in Fig. 9, the cost to set up the covering modeled network is highest and the value of f_4 is the lowest at the same time. This is consistent with what mentioned, better to support the humanitarian relief, higher the cost will be.

By the Fig. 9 and Fig. 7 (a), we can find that there are many edges cross the Central Mountain Range which full of mountains above 3,000 meters. The FM_1 operator does work and shows the violation has been avoided in Fig. 7 (b). The third experiment is about the disaster simulation. We have two modes to estimate the effect of earthquake, distributed demand and spot demand model as shown in Fig. 6 (a) and (b). It implies that the design of relief network will be biased if the historical data of disasters is a part of the input.

For hierarchical models in the literatures, the level is usually fixed without the consideration of uneven population distribution. Therefore, it is not necessarily applicable to the unbalanced distribution of population in urban and rural areas. In Fig. 8, no matter 10-level or 3-level, both of them are not really right to the real needs. Worse, the faults (gaps) happen easily once the designated level is too high. However, if the designated level is too short, the relief network cannot be benefited with the agglomeration and the transient influx of donation and contribution cannot be effectively absorbed, neither. In fact, more levels the network has, farther the transport will be. That is, both of the discount factor α and λ reduction are keys to form the hierarchical structures. These two factors can also be the clue to decide whether to invest in the designed network or not. In Fig. 10 (a), this network only has 2 levels because there is no support of rising power. It cannot form a higher hierarchy by itself. For Fig. 10 (b), this 3-level network is formed naturally. Since the population of Taipei city is the most crowed area in Taiwan, most of level 2 hubs are located in this area. That is the reason having some distant edges from south to north but with amalgamative transportation.

The over-constrained problem is usual in the design of network. We make the statistics about the four different kind of infeasible solutions including geography, level-skipping, dangling nodes (without suitably allocated to some warehouse or hub), and redundant capacity. At the same time, we slightly relaxed the restriction about the redundant capacity of

(a) (b) (c)

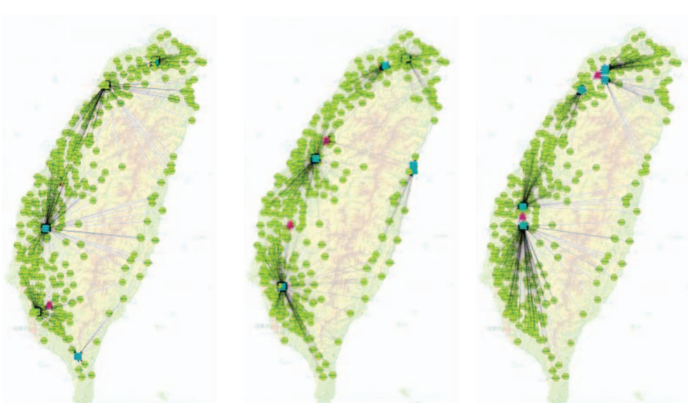

Fig. 9. (a) A 2-level covering relief network with cost 481160.7. (b) A 2-level 2-6-center relief network with cost 467673.8. (c) A 2-level 2-6-medium relief network with cost 401865.7.

(a) (b)

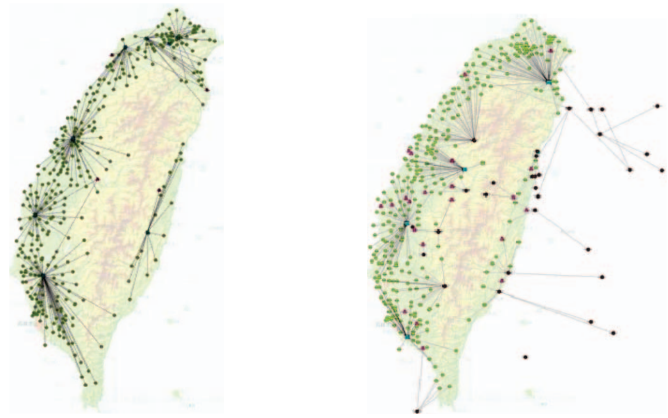

Fig. 6. (a) A 2-level covering relief network with distributed demand model. (b) The spot demand model is used for same network configurations. Those nodes outside Taiwan are the epicenters. The associated hubs are pointed to those nodes for which they are responsible in the disaster relief.

(a) (b)

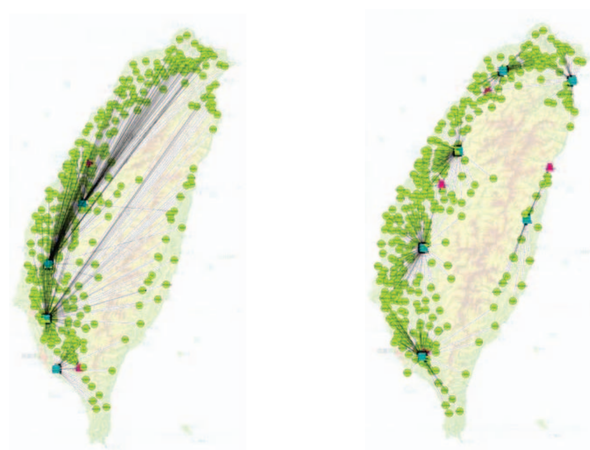

Fig. 7. (a) A covering relief network without FM_1 modification. (b) A covering relief network with FM_1 modification.

(a) (b)

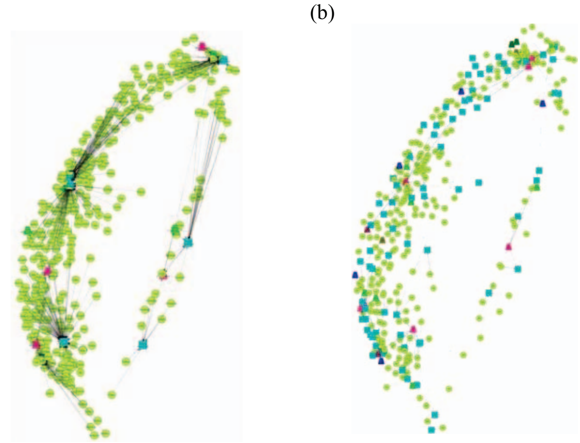

Fig. 8. (a) A fixed 3-level hierarchical hub covering network with cost 7,835,444. (b) A fixed 10-level network and the cost is 39,285,300.

warehouses and hubs but not asked for full allocation. We got the lower and better average cost but with a little higher ratio of infeasible solutions as shown in Fig. 11 (b). It shows that the capacity is one of keys to affect the network configuration. Also, the relationship between different constraints is subtle.

The hybrid variant improved by local search is usually better than the simple GA. Yet it only wastes the effort if without the knowledge about the search space. Interestingly, we seldom know the landscape of searching space for some problem in advance. We thus replace local search with automatic loci swap. After the swap, the content of chromosome is still the same but with different loci view. The hierarchical trees are more compact with more cross inter-level and inter-tree links as shown in Fig. 12(a). However, it is possible to bring in the infeasible solution at the same time as shown in Fig. 12(b). Especially, the peaks happened at generation 855 when the population turned to another searching direction, i.e. another loci view.

Finally, we examine the combined result with adaptive contest involving the actual cost function f_1, nonlinear-weighted cost function f_2, min-max hop distance function f_3, and disaster simulation f_4. In Table 1, 1-FL, NFL, LS, and AC mean one-fixed level, non-fixed level, loci swap, and adaptive contest separately. We can find NFL+LS+AC has the lowest network and relief cost when the 1-FL has the highest network cost and NFL has the highest relief cost. No surprisingly, both the loci swap and adaptive contest bring improvements. However, the loci swap has more effect on exploration with major improvement and adaptive contest has more effect on exploitation with minor adjustment. The result shows the cost-effective responsibility to the disaster relief.

Table 1
THE COMPARISON OF AVERAGE COST FOR GA VARIANTS

Variants	Network cost	Relief cost
1-FL	3,593,997	1,388,563
NFL	3,355,234	1,648,154
NFL+LS	3,067,792	1,039,684
NFL+LS+AC	2,986,694	974,483

The averages were taken from 25 repeated experiments. Smaller the value, better the result.

VI. CONCLUSIONS

The adaptive contest supports softness of the reference model and makes it practical. Also by well-designed GA operators and the loci swap, the HRGA is more effort-saving, tolerant, and flexible because of fewer unnecessary infeasible solutions, more intelligent processing and interpretation of chromosome. The experimental results indeed show the feasibility and benefits by our guess which is the proposed reference model which is a new hybrid facility location model with non-fixed levels, shortest-longest radiuses, limited capacities, least warehouses and hubs, and uneven hierarchies. For all of the experiments, real data is the main source though with some hypothetical scenarios. It implies that both of the developed hybrid model and HRGA are worth to be referred or adopted by the relief organizations.

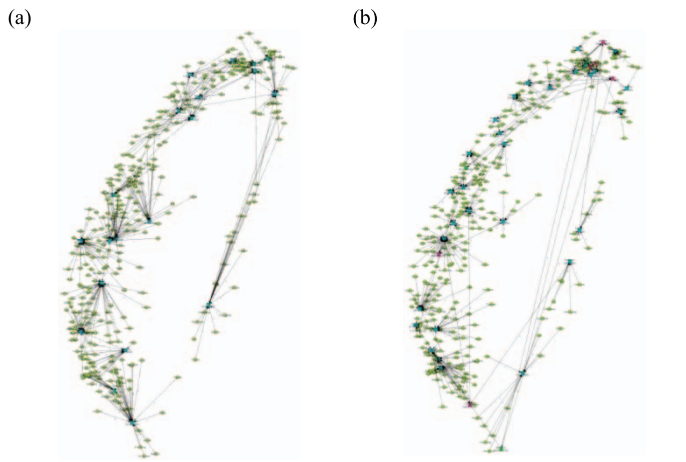

Fig. 10. (a) A 2-level relief network. (b) A relief network with 3-level is naturally formed by the α discount and λ reduction.

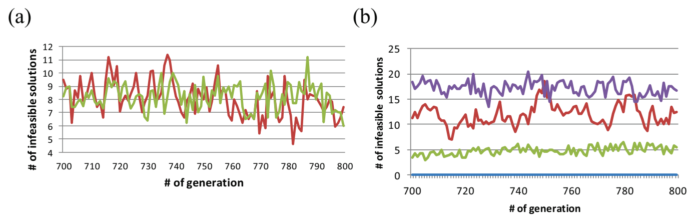

Fig. 11. (a) The statistics of infeasible solutions from generation 700 to 800 without the constraint of redundant capacity. (b) The statistics of infeasible solutions from generation 700 to 800 with the relaxation of redundant capacity constraint. The blue, green, red, and purple lines represent number of violations in geography, level-skipping, dangling nodes, and redundant capacity separately. The violation of redundant capacity represented by purple line appears in (b).

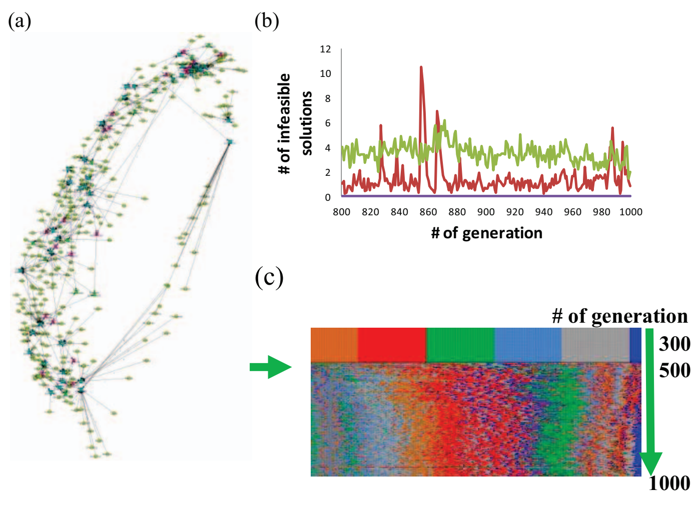

Fig. 12. (a) A 3-level network with more distinguished and compact hierarchical trees. (b) It is the statistics of infeasible solutions from generation 800 to 1000. (c) The gene loci with different color label were mixed instantly and continuously after the designated generation 500 to swap where the direction of evolution is downward for each horizontal chromosomes.

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