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Transportation Research Part E 43 (2007) 673–686
TRANSPORTATION RESEARCH PART E
www.elsevier.com/locate/tre

Multi-objective optimal planning for designing relief delivery systems

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Received 20 December 2005; received in revised form 27 July 2006; accepted 28 October 2006

Abstract

The fatal earthquake on September 21, 1999 caused significant damages to Taiwan, which made the national government focus on strengthening relief systems regarding natural disasters. Disaster prevention, protection, and reconstruction are the major areas of focus to reduce human suffering and damage from disasters. A key point is the ability to enhance the distribution of relief materials effectively. In this study, we construct a relief-distribution model using the multi-objective programming method for designing relief delivery systems in a real case. The model features three objectives: minimizing the total cost, minimizing the total travel time, and maximizing the minimal satisfaction during the planning period. The first two objectives pursue the efficiency goal, whereas the third pursue fairness – making best effort to ensure relief commodity delivery to all demand points. Results of an empirical study are presented and suggestions are given for future research.

Keywords: Earthquake; Multi-objective programming; Natural disaster; Relief distribution; Relief systems

1. Introduction

Although minor earthquakes occur nearly every day, the effects of a strong earthquake are devastating. The Shaanxi Earthquake, the deadliest earthquake in the history, killed 830,000 in rural China in 1556. Recent fatal earthquakes took place in Taiwan in September 1999, India in January 2001, Southeastern Iran in December 2003, Sumatra in December 2004, and Pakistan in October 2005. Earthquakes have been one of humankind's major enemies in the battle against natural disasters. The United Nations, public and private sectors have established many disaster-prevention or disaster salvaging centers or programs. The difficulty

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1366-5545/$ - see front matter
doi:10.1016/j.tre.2006.10.012

with natural disasters like earthquakes is that even though thousands of networked seismograph stations are installed around the world with powerful computers continuously analyzing the data, we are still unable to predict when and where the earthquake will strike. Therefore, the most effective method to reduce the damage of a disaster is disaster-prevention through research, monitoring, dissemination of information, and education. Information coordination between related organizations is valuable.

Once an earthquake strikes, effective disaster salvaging efforts can reduce the damage, reduce the number of lives lost, and bring relief to surviving victims. These include the establishment of a rescue command center, collection of information about the disaster area, identification of appropriate sites for shelters, determination of the best evacuation routes, transportation for evacuation and delivery of relief material, installation of medical and fire-prevention and emergency construction facilities. This study will concentrate on how to distribute relief material effectively and fairly. By fairness we mean that best efforts are made to ensure that the required relief materials are distributed to all demand points.

Sato and Ichii (1996) investigated the efficiency of evacuations. Bakuli and Smith (1996) proposed resource allocation in state-dependent emergence evacuation networks. Li et al. (1997) investigated crisis-management procedures, such as traffic-control on highways. Tzeng and Chen (1999) conducted a study on scheduling programming for restoration, construction and salvaging work for road networks. Although these studies provided insight into various disaster recovery efforts, the distribution of emergency relief was not properly addressed. This study will concentrate on the effectiveness and fairness of the overall distribution system to avoid the oversight of critical but difficult-to-reach areas in the real world. A fuzzy multiple objective model was used in this study and applied to a case study. Based on this case study, the corresponding measures needed for implementing the model has been put forward with additional scenario simulation. The model can be used to create local operational procedures as well as a part of a larger integrated relief distribution application. Further study can be conducted to integrate this model into a comprehensive decision support system for disaster relief.

The remainder of this paper is organized as follows. The features of the relief distribution systems are described in Section 2. A relief commodity distribution model with three aspects: economical – (minimal total cost), effective – (shortest total travel time), and fair – (maximal satisfaction of fairness), is derived in Section 3. An empirical case is presented to demonstrate the feasibility and effectiveness of this model in Section 4. Conclusions and recommendations are summarized in Section 5.

2. Characteristics of relief distribution systems

General physical distribution systems for business consider material items, cost of materials, number of vehicles, modes of transportation, number of depots, demand of materials, transportation networks, vehicle capacity, travel time of the route, and various operational modes. Some objectives of the physical distribution systems are to find a combination of those variables that minimizes total traveling time, minimizes size of vehicle fleet, maximizes service capacity, and minimizes fixed and variable costs.

Similar to general physical distribution systems, relief distribution systems also consist of three separate parts: demand, supply, and transportation. The collection points of commodities in non-devastated areas play the role of supply, while the demand points are the devastated areas where relief is provided to victims who play the role of customers. Additionally, large-scale commodities distribution depots near the demand point or the devastated areas play the role of distribution center. The only difference is that the distribution depots are temporary storage points instead of a permanent distribution warehouse.

Another characteristic of a disaster salvaging operation is that, instead of driving for profit in business, the operators of disaster salvage are often government agents or nonprofit organizations pursuing efficiency and fairness.

In the event of a disaster, decisions have to be made in a very short time and are based on limited and often incomplete information. Since a relief-distribution system can encounter rapid changes in circumstances, the operator may have to take necessary and emergency measures in order to minimize further damage and calm those affected, through the issuing of emergency orders, confiscation of civilian vehicles for emergency use, and closing of unsafe roads. The comparison of the features between the relief-distribution and regular distribution systems is presented in Table 1.

Table 1
Comparison of general and relief distribution systems

Comparison Items	General distribution systems	Relief distribution systems
System objectives	Maximize profit	Fairness and efficiency
Dimensional role	Factories Distribution centers Customers	Collection points for commodities Transfer depots for commodities Demand points of commodities
Facility characteristics	Regular facilities Substantial/tangible existence	Temporary facilities
Scheduling plan	Long term: location Median-term: vehicle-fleet size Short-term: scheduling	Urgent decisions based on available information
Trade-offs between algorithm-efficiency and optimization	Paying attention optimization	Emphasis of algorithm efficiency
Delivery models	Round-trip delivery; Circulating delivery	Round-trip delivery

3. Relief distribution model

The mathematical model of the disaster salvage distribution systems is presented in this section.

3.1. Assumptions

(1) We will consider only those devastated areas that still are accessible through the current road network, while disregarding those areas that are completely isolated and would require helicopters or other extraordinary means of relief distribution.
(2) Relief distribution considered in this system consists only those regular daily commodities and not those must be kept cold or requires other special transportation equipment.
(3) We assume the availability and accessibility of information such as the quantity of material needed and number of people in each of the devastated areas, situation of relief distribution, road condition, and restoration schedule if damaged.
(4) Changing characteristics of disaster salvaging such as the needs of the affected people and the availability of roads are considered constant within a discrete slot of timing. The time slot defined will be sufficient to allow complete distribution and allocation of all the relief supplies in a given shipment but not so extended that delays and procrastination could occur.
(5) The operator has the authority to mobilize enough military or civilian vehicles to assist the relief distribution, thus, there is no limit to the scale of vehicle fleet.

3.2. Model establishment

The design of the relief distribution systems is shown in Fig. 1, and the relief transfer depots are treated as the bridge between the upper-stream and lower-stream distribution system. As a whole, there are altogether T planning periods, K items of relief commodities, I collection points and J demand points. The purpose of the design is to resolve for each L candidate locations as the transfer depots, so that we can investigate the efficiency of and identify the optimal distribution systems.

3.2.1. Symbol explanation

Most of the parameters and variables employed in this model are time-related except the setup costs (FC) of the candidate points for relief transfer depots, the weight of the relief items (W), and the binary variable z that is used to indicate if the relief candidate location is selected to be a transfer depot. The definitions of parameters and variables specified in this study are summarized in the following.

3.2.1.1. Explanation of parameters and variables.

$AD_{k,j}(t)$ In period t, the amount of item k actually required by each demand point j;

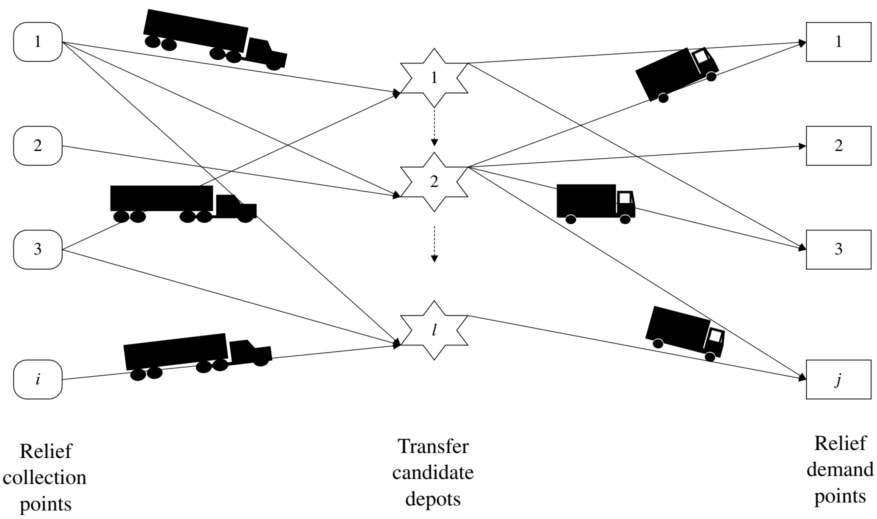

Fig. 1. The relief distribution system.

- $AS_{k,i}(t)$ In period t, the amount of item k actually available at collection point i;
- $c_i(t)$ Available truck capacity in period t at relief collection point i (capacity/car);
- $c_l(t)$ Available truck capacity in period t at transfer point l (capacity/car);
- $C_{il}(t)$ Unit transportation cost in period t, from collection point i to transfer point l (dollar/car);
- $C_{lj}(t)$ Unit transportation cost in period t, from transfer point l to demand point j;
- $D_{k,j}(t)$ Amount of commodity k needed for demand point j in period t (unit of calculation for k material);
- FC_l The setup cost in dollars (US or NT$?? Be specific) of the relief transfer depot l;
- $ms_k(t)$ In period t, the least satisfaction score among demand points with regard to the item k after the relief distribution;
- $R_{il}(t)$ The travel time in period t, from collection point i to transfer point l (h);
- $R_{lj}(t)$ The travel time in period t, from transfer depot l to demand point j (h);
- $S_{k,i}(t)$ The amount collected in period t of the item k at the collection point i;
- $s_{k,j}(t)$ In period t, the satisfaction score for commodity k at demand point j;
- $TC_{il}(t)$ In period t, the total transportation cost (dollar) from collection point i to transfer candidate depot l;
- $TC_{lj}(t)$ In period t, the total transportation cost (dollar) from transfer candidate point l to demand point j;
- $T_{il}(t)$ In period t, the travel time from the collection point i to actually sent the commodity to the transfer candidate depot l. If the commodity is actually sent from the collection point i to transfer candidate depot l, then $T_{il}(t) = R_{il}(t)$, otherwise its value is zero;
- $T_{lj}(t)$ In period t, the travel time from the transfer candidate depot l *to* actually sent the commodity to the demand point j. If the transfer depot l does have relief commodities to be sent to the demand point j, then $T_{lj}(t) = R_{lj}(t)$, otherwise its value is zero;
- W_k The package size (volume) of each package of commodity k;
- $x_{k,lj}(t)$ In period t, this indicates the amount of item k transported from transfer candidate depot l to demand point j;
- $y_{k,il}(t)$ In period t, the amount of relief item k at collection point i that is sent to transfer candidate depot l;
- z_l Whether or not the candidate point l is chosen as the transfer depot, with 0 indicating it was not to be chosen, and 1 to be chosen.

3.2.2. Distribution model

The model is constructed to achieve the following three objectives: the least total cost f_1, the minimum travel time f_2, and finally the maximum satisfaction or fairness f_3.

$$\min f_1 = \sum_l FC_l \times z_l + \sum_t \sum_i \sum_l TC_{il}(t) + \sum_t \sum_i \sum_j TC_{lj}(t) \tag{1}$$

$$\min f_2 = \sum_t \sum_i \sum_l T_{il}(t) + \sum_t \sum_i \sum_j T_{lj}(t) \tag{2}$$

$$\max f_3 = \sum_t \sum_k ms_k(t) \tag{3}$$

s.t.

$$\sum_l \sum_j x_{k,lj}(t) \leqslant \sum_j AD_{k,j}(t) \text{ and } \sum_l \sum_j x_{k,lj}(t) \leqslant \sum_i AS_{k,i}(t) \quad \forall t,k \tag{4}$$

$$\sum_i y_{k,il}(t) = \sum_j x_{k,lj}(t) \quad \forall t,k,l \tag{5}$$

$$\sum_l x_{k,lj}(t) \leqslant AD_{k,j}(t) \quad \forall t,k,j \tag{6}$$

$$y_{k,il}(t) \leqslant M \times z_l \quad \forall t,k,i,l \tag{7}$$

$$x_{k,lj}(t) \leqslant M \times z_l \quad \forall t,k,l,j \tag{8}$$

$$\sum_l y_{k,il}(t) \leqslant AS_{k,i}(t) \quad \forall t,k,i \tag{9}$$

$$y_{k,il}(t) \in \{0,1,2,\ldots\} \quad \forall t,k,i,l \tag{10}$$

$$x_{k,lj}(t) \in \{0,1,2,\ldots\} \quad \forall t,k,l,j \tag{11}$$

$$z_l \in \{0,1\} \quad \forall l \tag{12}$$

The three objectives in the proposed relief distribution model are indicated by Eqs. (1)–(3), respectively, and are explained in detail in following paragraphs.

Objective (1): Minimize total cost – "economy" objective f_1
Costs include setup and operational costs of the transfer depots and transportation of relief commodities among the supply points and demand points. Given that the sizes of relief shipments vary, their actual size must be available so that the calculation unit of the relief can be standardized. The transportation cost could be determined after calculating the frequency of shipments. The upper-stream transportation cost TC_{il} is computed using Eq. (13), so the lower-stream transportation cost TC_{lj} can also be computed in a similar fashion.

$$TC_{il}(t) = C_{il}(t) \times \left\lceil \frac{\sum_k W_k \times y_{k,il}(t)}{c_i(t)} \right\rceil \quad \forall t,i,l \tag{13}$$

where $\lceil x \rceil$ indicates the upper-bound function (ceiling function), the smallest integer larger than or equal to x, such as $\lceil 4.8 \rceil = 5$.

Objective (2): Minimize total travel time – "effectiveness" of distribution f_2
Since the travel time among collection points, transfer depots, and demand points are already known, the calculation of travel time is required only if there is any shipment between collection point and transfer point, then sum up the actual travel time used. The transportation time T_{il} of the upper-stream can be calculated using Eq. (14), while T_{lj} of the lower-stream can be found in a similar fashion.

$$T_{il}(t) = \begin{cases} 0, & \text{if} \quad \sum_k W_k \times y_{k,il}(t) = 0 \\ R_{il}(t), & \text{if} \quad \sum_k W_k \times y_{k,il} > 0 \end{cases} \tag{14}$$

Objective (3): Maximize satisfaction f_3

The primary purpose of this objective is to maximize the satisfaction of fairness and to minimize unfair distribution. In this model, no limit is set to the satisfaction score because "if there is higher satisfaction in certain relief distribution, there must be some concession in other relief items", and we will treat each relief item independently. Thus, the idea of the weighting method is employed to sum up the least satisfaction value of each relief item in every period of time so as to reduce the number of objective equations. The satisfaction and least satisfaction are calculated using the following equations.

$$s_{k,j}(t) = \frac{\sum_l x_{k,lj}(t)}{AD_{k,j}(t)} \quad \forall t,k,j \tag{15}$$

$$ms_k(t) = \min_j\{s_{k,j}(t)\} \quad \forall t,k \tag{16}$$

Now we will explain the constraints. Eq. (4) means insufficient goods are not allowed to lay idle and you cannot ship what you do not have, and the equation can be rewritten as $\sum_l\sum_j x_{k,lj}(t) \leqslant \min\left[\sum_j AD_{k,j}(t), \sum_i AS_{k,i}(t)\right] \forall t,k$; Eq. (5) means all goods are shipped in and out of transfer depots in the same period; Eq. (6) means that we do not over-ship any one item; Eqs. (7) and (8) are used to determine the selection of transfer depots among candidate locations; Eq. (9) means ship only available goods at collection points; Eqs. (10) and (11) reveal quantities predetermined for each item.

In a relief system, the top priority would be to meet the needs of the victims. Although cost remains a consideration, it would be unacceptable to have relief supplies lay idle in the system to save transportation costs or travel time. Therefore, during every period of t, the total amount received at every relief demand point should be equal to the total amount shipped out of the collection points for every item as indicated in Eq. (5). In planning, we assume that the only things the victims need are the relief supplies. If the provisions are not delivered in that period, however, it can be made up in the next as there would not be any so-called giving up time validity. Eqs. (17) and (18) shows, in every period t, the supply capability in each commodity supply point i and the calculation of the actual demand in each of the relief demand point j.

$$\begin{cases} AS_{k,i}(t) = S_{k,i}(t) & \forall k,i \quad \text{when} \quad t=1 \\ AS_{k,i}(t) = S_{k,i}(t) + \left[AS_{k,i}(t-1) - \sum_l y_{k,il}(t-1)\right] & \forall t,k,i \quad \text{when} \quad t \geqslant 2 \end{cases} \tag{17}$$

$$\begin{cases} AD_{k,j}(t) = D_{k,j}(t) & \forall k,j \quad \text{when} \quad t=1 \\ AD_{k,j}(t) = D_{k,j}(t) + \left[AD_{k,j}(t-1) - \sum_l x_{k,lj}(t-1)\right] & \forall t,k,j \quad \text{when} \quad t \geqslant 2 \end{cases} \tag{18}$$

3.3. Model modification and resolution

After the model was constructed based on real behavior, we needed an efficient method to obtain a solution. Fuzzy programming introduced in Zimmermann, 1978, which combined with the idea of fuzzy logic provides a method for uncertainty analysis of achievement level for each objective. Although the importance of objective 3 is known to be higher than those of the other two objectives, the weight relationship among these three objectives cannot be clearly defined. As a result, this study has employed fuzzy multi-objective linear programming (Tzeng and Teng, 1998; Chen and Tzeng, 1999; Tzeng and Chen, 1998, 1999; Tzeng et al., 2006) of max-min operation to re-write the mathematical equation for resolution. Thus, after the resolution for a single objective has been conducted to establish a multi-objective pay-off table, the membership function of the best (optimal) value (f_i^+) and the worst value (f_i^-) of each of the objectives can be then be found.

Since objective 3 is the maximization of the least satisfaction, its ideal value must be that the relief will be evenly distributed to each of the demand points regardless of cost. Therefore, the value of the ceiling limit (upper boundary) of objective 3 should be determined, and every kind of the relief items among all of the relief demand points in every period will suffice. Its value will be KT, where K is the total amount of relief items and T the total number of planned periods.

Within the relief distribution systems, the most important purpose will be to satisfy the current needs of the surviving victims as much as possible as well as reduce the damage of aftershocks. As understood, considerations of time and money are not the ultimate aims but merely soft constraints in order to ensure that resources are utilized effectively. Hence, (f_3^+) is designated for KT so that objective 3 will become the critical path for the system resolution, making the system achieve its optimal performance in order to demonstrate its importance. As follows, the objective Eqs. (1)–(3) of the distribution model in Section 3.2.2 can be rewritten as Eqs. (19)–(22) for achieving the maximal satisfaction level, while the original constraints remain intact as in Eqs. (4)–(12):

$$\text{Max} \quad \lambda \tag{19}$$

s.t.

$$\frac{f_1^- - f_1}{f_1^- - f_1^+} \geqslant \lambda \tag{20}$$

$$\frac{f_2^- - f_2}{f_2^- - f_2^+} \geqslant \lambda \tag{21}$$

$$\frac{f_3 - f_3^-}{f_3^+ - f_3^-} \geqslant \lambda \tag{22}$$

Eqs. (4)–(12)

4. Case analysis of the relief-distribution operations

Disaster salvaging is like field combat, the final outcome of the strategy depends on whether it can be carried out effectively. Thus, this section will make use of scenario simulation to elaborate on how to utilize the constructed model for integral relief distribution, so that the operation procedures, as well as subsequent issues, can be established for further studies.

4.1. Information content and data collection

The values of parameters of the model have to be established before planning. Data collection can be performed during ordinary days, feedback during the disaster, salvaging period and need analysis of the feedback during the current disaster or from previous experiences. They are classified in Table 2 according to different work items.

4.1.1. Pre-operation stage

Data collection in the pre-operation stage refers to the data collected during ordinary days, which includes the work contents and the suggested methods of data collection.

(1) Calculate each relief commodity size volume equivalent
Among each of the daily commodities, choose the size from one of them to be used as the basic unit for measuring volume (the size of a sleeping bag is used as the criterion for measuring volume equivalents in this study). The volume size equivalent of each relief commodity can found in Table 3.
(2) Establish the electronic map
Electronic maps made of Taiwan's entire highway network identify the shortest routes and alternative routes quickly and easily. This study employs the "Taiwan Island 1/25/2000 Transportation Network Numerical Value Map" made by the Taiwanese Transportation Institute of the Ministry of Transportation and Communications.
(3) Investigate the coordination capability for emergency relief in all affected areas
Coordination capability for emergency relief would be one of the criteria for the prediction of supply and demand in each of the areas after a disaster. Questions about daily commodities could include: what is the area's primary staple crop? Are any warehouses available for storage? Does the area have any warehouses of factories that produce daily necessities?

Table 2
Information nature

Stages	No.	Work contents	Dependencies
Pre-operation	1a	Calculate each relief commodity size volume equivalent (W_k)	No
	1b	Establish the electronic map	No
	1c	Investigate the coordination capability for emergency relief in the whole area	No
	1d	Calculate each kind of truck capacity equivalent	No
Information transmission of disasters	2a	Estimate the situation of road destruction and the time of road restoration	No
	2b	Survey the degree of damage in each area	No
	2c	Forward the location of each commodity demand point (j)	2b
	2d	Identify the number of victims who needs care at each commodity demand point	2c
Plan and analysis	3a	Predict the commodity demand for each commodity demand point ($D_{k,j}(t)$)	1c, 2d
	3b	Select a location for each commodity demand point (i)	2b
	3c	Determine the commodity supply capability for each commodity collection point ($S_{k,i}(t)$)	1c, 3b
	3d	Determine the support vehicle category sending relief commodity for each commodity collection point	3b
	3e	Determine the support truck capacity sending relief commodity for each commodity collection point ($c_i(t)$)	1d, 3d
	3f	Select the location for the candidate points of each commodity transfer depot (l)	2c, 3b
	3g	Analyze the shortest route from the candidate points of each commodity transfer depot to the relief demand point	1b, 2a, 2c, 3f
	3h	Analyze the shortest route from the relief collection point to the candidate points of each commodity transfer depot	1b, 2a, 3b, 3f
	3i	Analyze the set up cost of candidate point of the relief transfer depots (FC_l)	3f
	3j	Determine the support vehicle category sending relief commodities for candidate points of each commodity transfer depot	3f
	3k	Determine the support truck capacity sending relief commodity for candidate points of each commodity transfer depot ($c_l(t)$)	1d, 3j
	3l	Calculate travel time from candidate points of each commodity transfer depot to each relief demand point ($R_{lj}(t)$)	3g
	3m	Calculate the unit transportation cost from candidate points of commodity transfer depot to each relief demand point ($C_{lj}(t)$)	3g
	3n	Calculate travel time from each relief collection point to candidate points of each commodity transfer depot ($R_{il}(t)$)	3h
	3o	Calculate the unit transportation cost from relief demand points to candidate points of each commodity transfer depot ($C_{il}(t)$)	3h

Table 3
Calculation of each relief commodity size volume equivalent

Item	Calculation Unit	Volume (cm^3)	Volume equivalent
Sleeping bag	EA (nylon sleeping bag)	$45 \times 25 \times 11 = 12{,}375$	1.00
Tent	EA (6–8 people yurt)	$70 \times 26 \times 15 = 27{,}300$	2.21
Mineral water	Box (1410 ml, 12 bottles)	$36 \times 26 \times 30 = 28{,}080$	2.27
Rice	Pack (5 kg packed rice)	$38 \times 25 \times 5.5 = 5225$	0.42
Instant noodle	Box (bowl instant noodle, 12 bowls)	$43 \times 29 \times 17 = 21{,}199$	1.71
Dry food	Box (nutrition biscuits, 30 packs)	$38 \times 27 \times 18 = 18{,}468$	1.49
Canned food	Box (glass canned food, 12 cans)	$29 \times 21 \times 5.8 = 3532$	0.29

(4) Calculate the truck capacity equivalent
The carrying capacity of a vehicle is affected by more than just the tonnage of the vehicle itself. Whether a truck has a canvas cover is one of many things to take into account. The primary military vehicles for distribution, for example, are the "Hummer" and "10 and 1/2 ton" with cover. The government provides the maximum distribution capacities of these vehicles. Vehicles provided by civilians, however, are usually small trucks without covers. Their largest height for carrying is dictated by article 4 of reg-

Table 4
Calculation of every kind of truck capacity equivalent

Vehicle name	Carry space (cm^3)	Carry equivalent
Military vehicle – Hummer	$280 \times 200 \times 140 = 7840{,}000$	634
Military vehicle – 10.5 ton	$600 \times 250 \times 175 = 26{,}250{,}000$	2121
Civilian truck – 1.5 ton	$231 \times 150 \times 130 = 4{,}504{,}500$	364

Remark: 1 sleeping bag volume = 1 equivalent.

ulation 79 of the "Traffic Safety Regulations of the Thoroughfare", which states that the height of carried goods "should not exceed 4 m, or 2.5 m for small vehicles, as measured from ground level" (see Table 4).

4.1.2. Disaster information transmission

The second type of information needed varies with the development of the situation after the disaster, and includes the work contents and the data collection types as follows:

(1) Estimate the extent of road destruction and the time of road restoration
Aside from investigative reports from each of the damaged areas, a bird's-eye view can be obtained by helicopter immediately after the disaster to determine the state of the traffic network in advance to deploying ground vehicles. Furthermore, time needed for road restoration for each of the important sections can then be estimated based on the manpower and equipment dispatched as well as the degree of damage.
(2) Survey each area
This mainly establishes a devastation-feedback system, which is conducted through a communication chain from lanes or villages to the central command unit to specify if there is any relief needs. The numbers of men, women, elderly, children, and the victims that need care should be reported.

4.2. Route planning and network analysis

The third dimension of information is obtained by planning and analysis on the database previously established in relation to the data forwarded from each of the devastated areas. The primary work contents are as follows:

(1) Predict the commodity demand
Estimates of possible demand for each of the daily necessities over specific periods of time are made based on emergency-coordination capability, the extent of devastation, and the age and sex combination of victims at the relief-demand points who need care. For example, it is important to determine how much food and water an average adult needs to survive.
(2) Plan the commodity collection depots
Once the extent of disaster is known, affected and non-affected areas can be delineated. Suitable locations such as the village or township office, or county or city administration centers, which people of the area would know well, can be established in non-devastated areas for relief-collection points. The private sector and members of the public can be encouraged to donate relevant daily necessities. In addition, once the location is chosen, the supply capacity of the area could be estimated based on the emergency coordination information of each area and plan for supporting vehicles for allocation.
(3) Set up the transfer depots
Once the location of each of the demand points is known and the collection points have been chosen, several large-scale transfer depots can be established at locations based on the extent of road damage and time for restoration. There are two principles for the establishment of a transfer depot:
a. The location should be prominent and be accessible through alternative roads;
b. There should be enough space to store, coordinate, and package relief commodities.

Once the candidate locations for transfer depots are selected, the cost for establishment can then be estimated and the allocation of supporting vehicles planned.

(4) Select the quickest route
Based on the distribution of commodity-demand point, commodity-collection point, and candidate points of transfer depots in correspondence with the information about road destruction and estimated timing for restoration, GIS software (i.e., MapInfo, TransCad, ARC/INFO) can be used on the electronic map to find the quickest distribution route in each period of time. Given that the distribution of relief is often an emergency, the government could enact stringent traffic-control measures; thus, unlike regular distribution, in which traffic volume is a variable, the speed could be exactly determined, giving better estimates for travel time along road sections. Meanwhile, the length and mode of vehicle can also be taken into account in order to estimate the unit transportation cost between two points.

4.3. Case illustration and data analysis

4.3.1. Case illustration

The case analysis focuses on Taichung, Nantou City, and Nantou County, which experienced a major earthquake on September 21, 1999. The demand points and supply points are shown in Table 5. The commodities beyond the domain of study would be gathered at Fongyuan for the northern areas (such as Taipei, Taoyuan, and Hsinchu) and at Douliou, Yunlin County, for the southern areas (such as Kaohsiung and Pingdong).

This study covers five collection points, eight demand points, and four transfer depots. Some areas perform multiple duties. For example, Fongyuan serves as both a supply point and a transfer depot, while Nantou is a transfer station as well as a demand point.

Relief for distribution includes sleeping bags, tents, mineral water, and four kinds of instant noodles that are distributed at four planned periods of time.

The case study takes the county and provincial road circuit into consideration, and each road section would be given a designated travel time. Then by using TransCAD software, the quickest route would be located. This case would simplify the restoration work on damaged roads by dividing it into three categories. As a result, the quickest travel time between two places could change.

The results of the quickest travel time, travel distance, number of victims in need of care in each area, mode of demand for every item of relief, and supply information are shown in Tables 6 and 7.

4.3.2. Data analysis and discussion

Using LINGO for analysis, Fongyuan and Nantou are selected as the sites for transfer depots based on low set up costs and their geographical locations. The location results in lower unit transportation cost and travel

Table 5
Research case locations

	Demand points		Supply points		Transfer depots	
1	Taichung city	Baseball field	Fongyuan city	Fongyuan stadium	Fongyuan city	Fongyuan stadium
2	Taiping city	Fire department	Dongshih township	Dongshih elementary school	Caotun township	Farmer association warehouse
3	Dali city	Dali city government	Chunghw city	Chunghw county government	Nantou city	Nantou county stadium
4	Nantou city	Nantou county stadium	Yuanlin township	Yuanlin township government	Mingjian township	Mingjian elementary school
5	Puli township	Fire department	Douliou city	Chung Shiou temple		
6	Kuoshin township	Kuoshin Street				
7	Chungliou township	township government				
8	Chushan township	township government				

Table 6
The results of commodity distribution between supply points and transfer depots

Supply points	Item		T1		T2		T3		T4	
			Fongyuan	Nantou	Fongyuan	Nantou	Fongyuan	Nantou	Fongyuan	Nantou
Fongyuan	Amount of Delivery (units of millions)	Sleeping Bags	14.66	0	37.54	0	46.92	0	0	0
		Tents	3.24	0	14.52	0	4.23	16.34	0.83	0
		Mineral water	12.00	0	15.36	0	0	15.36	13.82	0
		Instant Noodles	26.99	0	34.55	0	33.88	0.67	3.50	0
	Distributed equivalent		95.21	0	163.58	0	114.22	72.13	39.19	0
	Times of delivery		5.00	0	8.00	0	6.00	4.00	7.00	0
Dongshih	Amount of Delivery (units of millions)	Sleeping Bags	0	0.51	1.23	0	1.44	0	0	0
		Tents	0.25	0.04	0.52	0	0	0	0	0
		Mineral water	0.30	0	0.36	0	0	0.36	0	0
		Instant noodles	1.54	0	1.85	0	0	1.85	0	0
	Distributed equivalent			0.61	6.36	0	1.44	3.98	0	0
	Times of delivery			1.00	2.00	0	1.00	1.00	0	0
Chunghwa	Amount of Delivery (units of millions)	Sleeping Bags	0	5.15	0	14.41	0	18.01	2.43	0
		Tents	0	0.79	0.16	2.01	0	0	0	0
		Mineral water	0.74	7.79	6.16	5.78	1.36	10.58	10.26	0.48
		Instant noodles	14.54	8.59	21.69	10.70	0	0.53	0	1.52
	Distributed equivalent			39.25	51.44	50.37	3.08	42.92	25.74	3.69
	Times of Delivery			2.00	3.00	3.00	1.00	7.00	5.00	1.00
Yuanlin	Amount of Delivery (units of millions)	Sleeping Bags	0	2.06	0	4.65	0	5.81	0	0
		Tents	0	0.43	0	0.73	0	0.95	0	0.10
		Mineral water	0	0.45	0	0.51	0	0.51	0	0.46
		Instant noodles	0	11.57	0	13.07	0	13.07	0	0
	Distributed equivalent			23.82	0	29.77	0	31.42	0	1.27
	Times of Delivery			4.00	0	5.00	0	5.00	0	1.00
Douliou	Amount of Delivery (units of millions)	Sleeping Bags	0	10.29	0.75	32.18	1.44	0	0	1.60
		Tents	0	2.74	0.06	10.88	0	0	0	0.25
		Mineral water	0	6.74	0	10.78	10.78	0	0	9.70
		Instant noodles	0	29.30	0.31	46.57	5.21	0	0	0
	Distributed equivalent			81.75	1.40	160.35	34.82	0	0	24.17
	Times of Delivery			4.00	1.00	8.00	2.00	0	0	4.00
Extra supply (units of million)		Sleeping Bags			−108.08[a]		−57.53		39.82	71.45
		Tents			−33.91		−16.80		36.06	40.65
		Mineral water			−22.25		−33.57		−39.85	−39.99
		Instant noodles			−58.27		−30.07		73.53	94.26

[a] Negative quantity of supply means there is an item shortage.

Table 7
The distribution results from transfer depots to demand points

Planning stage	Transfer depots	Amount of delivery (units of millions)				Distributed equivalent	Times of delivery	Satisfaction (%)			
		Sleeping bag	Tents	Mineral water	Instant noodle			Sleeping bag	Tents	Mineral water	Instant noodle
		Taichung									
T1	Fongyuan	4.4	1.0	3.8	13	37	2	23	18	56	61
	Nantou	0	0	0	0	0	0				
T2	Fongyuan	12	3.9	5.3	3.5	39	2	61	63	53	81
	Nantou	0	0	0	14	24	6				
T3	Fongyuan	9.9	2.9	5.3	7.5	41	2	100	100	49	100
	Nantou	0	0	0	0	0	0				
T4	Fongyuan	0.5	0.2	0	0.7	2.1	1	100	100	47	100
	Nantou	0	0	4.7	0	11	3				
		Dali									
T1	Fongyuan	1.8	0.9	3.5	12	32	2	23	18	56	61
	Nantou	2.3	0	0	0	2.3	1				
T2	Fongyuan	0	2.7	4.9	16	45	3	61	63	53	81
	Nantou	11	1.0	0	0	14	4				
T3	Fongyuan	9.3	0	1.3	3.0	17	1	100	100	49	100
	Nantou	0	2.7	3.6	4.0	21	6				
T4	Fongyuan	0.5	0	4.4	0	11	2	100	100	47	100
	Nantou	0	0.2	0	0.6	1.4	1				
		Chungliao									
T1	Fongyuan	1.8	0	0	0	1.8	1	23	18	56	61
	Nantou	0	0.4	1.5	5.0	13	4				
T2	Fongyuan	0	0	0	0	0	0	61	63	53	81
	Nantou	4.9	1.6	2.1	7.0	25	7				
T3	Fongyuan	4.0	0	0	3.0	9.2	1	100	100	49	100
	Nantou	0	1.2	2.1	0	7.4	3				
T4	Fongyuan	0	0	0	0	0	0	100	100	47	100
	Nantou	0.2	0.1	1.9	0.3	5.2	2				
		Puli									
T1	Fongyuan	0	0	0	0	0	0	23	18	56	61
	Nantou	7.2	1.6	6.1	20	59	15				
T2	Fongyuan	20	6.4	8.5	29	102	5	61	63	53	81
	Nantou	0	0	0	0	0	0				
T3	Fongyuan	0	0	0	0	0	0	100	100	49	100
	Nantou	16	4.7	8.6	12	67	19				
T4	Fongyuan	0	0.3	7.7	1.1	20	4	100	100	47	100
	Nantou	0.9	0	0	0	0.9	1				

Planning stage	Transfer depots	Amount of delivery (units of millions)				Distributed equivalent	Times of delivery	Satisfaction (%)			
		Sleeping bag	Tents	Mineral water	Instant noodle			Sleeping bag	Tents	Mineral water	Instant noodle
		Taiping									
T1	Fongyuan	2.6	0.6	2.3	7.5	22	2	23	18	56	61
	Nantou	0	0	0	0	0	0				
T2	Fongyuan	7.3	2.3	3.2	10	37	2	61	63	53	81
	Nantou	0	0	0	0	0	0				
T3	Fongyuan	6.0	0	3.2	4.5	21	1	100	100	49	100
	Nantou	0	1.7	0	0	3.8	2				
T4	Fongyuan	0.3	0.1	2.8	0.4	7.7	2	100	100	47	100
	Nantou	0	0	0	0	0	0				
		Nantou									
T1	Fongyuan	0	0	0	0	0	0	23	18	56	61
	Nantou	8.5	2.0	7.3	24	–	–				
T2	Fongyuan	0	0	0	0	0	0	61	63	53	81
	Nantou	24	7.5	10	34	–	–				
T3	Fongyuan	12	0	0	14	36	2	100	100	49	100
	Nantou	7.7	5.6	10	0	–	–				
T4	Fongyuan	1.1	0.3	9.1	1.3	25	4	100	100	47	100
	Nantou	0	0	0	0	–	–				
		Chushan									
T1	Fongyuan	2.0	0.5	1.7	5.7	17	1	23	18	56	61
	Nantou	0	0	0	0	0	0				
T2	Fongyuan	0	0	0	0	0	0	61	63	53	81
	Nantou	5.6	1.8	2.4	8.0	29	7				
T3	Fongyuan	4.6	1.3	0	3.4	13	1	100	100	49	100
	Nantou	0	0	2.4	0	5.5	2				
T4	Fongyuan	0	0	0	0	0	0	100	100	47	100
	Nantou	0.3	0.1	2.2	0.3	5.9	2				
		Koushin									
T1	Fongyuan	2.0	4.6	1.7	5.7	17	1	23	18	56	61
	Nantou	0	0	0	0	0	0				
T2	Fongyuan	0	0	0	0	0	0	61	63	53	81
	Nantou	5.6	1.8	2.4	7.9	28	7				
T3	Fongyuan	4.5	0	2.4	3.4	16	1	100	100	49	100
	Nantou	0	1.3	0	0	2.9	1				
T4	Fongyuan	0	0	0	0	0	0	100	100	47	100
	Nantou	0.3	0.1	2.1	0.3	5.8	2				

time from most of the demand and supply points, such as from Taichung, Taiping, Dali, and Dongshih to Fongyuan, and from Yuanlin to Nantou to be the minimal. In addition, since Fongyuan is also acting as the collection point and Nantou the demand point, the choice of these two places would enhance the integral performance of the system. Aside from the disparity of sources regarding supply as shown in Table 7, Fongyuan transfer depot has to move part of its relief to the Nantou transfer depot to meet the demands of Nantou. Considering the travel time and transportation cost, the Fongyuan transfer depot would mainly collect and distribute relief supplies to Taichung, Taiping, Dali, and Dongshih, while Nantou would be responsible for Puli, Kuoshin, Chungliou, Chushan, and Yuanlin. Chunghwa is not selected as a transport point because it is located in the middle of Taichung and Nantou, and it does not significantly affect the system.

The ranking of achievement level of the three objective values are 0.93, 0.82, and 0.65, respectively, while the objective 3 is the lowest one. Therefore, objective 3 is the bottleneck of the system in line with the fact that this model will not compromise the equity of relief distribution in considering cost and time. Yet an examination of Table 7 reveals that in order to increase the achievement level of objective 3, the result of relief distribution is even when supply is over demand. In other words, the relief given to all of the demand points in every period reveals a certain fixed ratio to its actual demand. Thus, the satisfaction of all of the demand points in each period of time obtaining a kind of commodity will be integral. Though the achievement level of objective 3 is merely 0.6527 because we deliberately choose the high value of $f_3^+ = TK = 16$.

As a whole, the final resolution not only rendered objective 3 to reach its optimum but also objectives 1 and 2 to rather certain achievement level under all of the constraints. Therefore, the results derived are reasonable and could be used by decision makers. If the ideal value of the objective 3 to maximize the minimal satisfaction is adjusted to (total planning period) × (total item for distribution), even when supply is below demand, it would still follow the same ratio of distribution to each of the demand points. After this, a suitable distribution route would then be located. The resulting analysis of the objective is in line with the results we have seen in reality. The decision maker can, based on the need of decision making, also select the optimal value of objective 3 at will and have it split between the evenly distributed result and (total period of planning) × (total item of distribution). In doing so, the importance of objective 3 is greater than that of the other two, yet neither is dominant. The actual achievement level of objective 3 will not reach 100%, while the achievement levels of the other two objectives can be improved.

5. Conclusions and recommendations

Relief distribution is one of the most important aspects of disaster salvaging. The features inherent in the relief-distribution systems found in this study are based on the assumption that the government has the authority to expropriate enough military or civilian vehicles to help with the distribution of relief and to control traffic during the period of relief distribution. We used fuzzy multi-objective programming to create an emergency relief distribution model for the reference of the decision maker. As a part of the entire disaster salvaging system, sufficiently correct information must be prepared and be available before applying the model.

The data content needed to be processed for each of the parameters is listed in Table 2, and Figure 2 elaborates on the priority and relationship of each procedure regarding the implementation of their content. Data collection was divided into the pre-operation stage, and following the disaster and with the analysis of the information compiled, the distribution can be determined. In order to test the feasibility and effectiveness of the method in this study, a real case study was used to illustrate the concepts described. Compatible measures needed for the execution of this model were put forward during the illustration for the reference of emergency relief distribution during and after a natural disaster. Further in-depth study is needed to provide steps and recommendations for each of the procedures and to develop a more representative method of estimation. This study provides some insights for the decision support system that must include a database of basic information on pre-operation items and geographic information.

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