Can Resource Sharing Improve Disaster Response Effectiveness? Evidence from West Sumatra Earthquake

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***Abstract*—In the aftermath of a disaster, it is common that various organizations get involved and resource scarcity exists. This paper deals with relief distribution and victim evacuation in response to a disaster and examines whether the response effectiveness can be made better by sharing vehicles and distribution centers. Based on the response that took place in Padang Pariaman District following the West Sumatra earthquake, two dynamic location-allocation models are built and subsequently tested with a series of computational experiments. Analysis of the effect size and suffering reductions of the experimental results makes it evident that the proposal of sharing vehicles and distribution centers improves the response effectiveness.**

Keywords— disaster response; resource sharing; dynamic location-allocation mathematical model

I. Introduction

It is common that various organizations get involved in dealing with a disaster once the disaster strikes [1]. Additionally, disasters frequently take place where resource scarcity exists [2]. In order to reduce the disaster effect towards its minimum level, the presence of various organizations and resource scarcity necessitates good coordination (see, for instance, [3], [4]). In a disaster context, coordination has been defined as "the relationships and interactions among different actors operating within the relief environment" [1]. One of resource coordination activities is resource sharing (see, e.g., [5]). Resource sharing includes sharing of vehicles and of temporary or permanent distribution centers.

This paper addresses the disaster response carried out in Padang Pariaman District following the West Sumatra earthquake that took place on 30th September 2009. The paper is primarily concerned with a proposal to improve the response practice. More specifically, the paper examines whether the response effectiveness can be made better by the sharing of vehicles and of distribution centers. In order to do so, two different dynamic location-allocation mathematical models, namely model I and model I_full, are built.

Following the West Sumatra earthquake, commodity relief distribution in Padang Pariaman District to its sub-districts was performed by the Agency of Social Affairs in the district. In each sub-district, the local government body was in charge of the relief distribution. Vehicles available for distribution purposes in a particular sub-district could serve disaster areas only in that sub-district. The local government body also decided the locations for temporary distribution supplies in the sub-district. The Agency of Health in the district, on the other hand, carried out injured victim evacuation. This agency also conducted allocation of incoming medical facilities to particular areas. Vehicles provided for evacuating injured victims – which were different from those vehicles for relief distribution – were able to serve injured victims in any sub-district. All these activities were reported in a regular joint meeting coordinated by an Implementing Unit for Disaster Management in the district and attended by all related agencies. The unit (and its supra-units at the provincial and national levels) had command authority to coordinate various agencies involved during the response phase of the disaster management.

II. Mathematical Models and Computational Experiments

For the purpose of generality, the following terms are used in the models. The term *region* is used to represent the whole district. A sub-district in the district is portrayed by the term *sub-region*. Each sub-region consists of a number of *disaster areas,* and a single *nagari* – a regional unit within a sub-district –is represented by each of these disaster areas.

General assumptions applied to both model I and model I_full are available in [6] and are re-provided, as follows.

Locations of disaster victims are represented as points, whereas the victims themselves are categorized into injured victims – which are treated individually and need to be evacuated – and injury-free sufferers – who are assumed to stay in the disaster areas and need to be supplied by commodity relief. At least one site with a distribution center – the site is selected at the beginning of disaster relief operation – and one site with either a temporary or existing medical facility are assumed to be available in every time period within the planning horizon. All of these locations and sites are assumed to be known. Activity of evacuating/relocating the injury-free sufferers, if any, is excluded from the study. Travel times between locations – including additional times needed due to road damage, congestion, and so on – are assumed to be known.

Transfer of injured victims from any medical facility to other medical facilities, if any, is not included in the models. Similarly, transportation of commodity relief from any distribution center to other distribution centers, if any, is also excluded from the models. The vehicles either for victim evacuation or for commodity relief distribution or for both activities are assumed to use particular sites as bases. All vehicles available at sites at the beginning of the planning horizon are presumed ready to be deployed to any site and are classified as "vehicles available at time point 0". As a consequence, all sites are assumed to have no vehicles at time point 0 of the first implementation of the model. All vehicles are assumed to have the same capacity due to their similarity in size.

Upon arriving at the disaster scene, both incoming medical facilities and incoming vehicles stay at least until the beginning of the next time period. A vehicle allocated to a site at the beginning of a certain time period serves the site during the whole of that period, and it is only possible for it to move to other sites at the beginning of the next period.

For each un-evacuated injured victim in each period, a penalty with the same value is given. A penalty with another constant value is also given for each unit of unmet type-2-commodity relief demands in each period. Supplies of any commodities, in the meantime, are set as unlimited.

Sets used in mathematical model I and model I_full are as follows.

- R Set of sub-regions, $R = \{1,2,\dots,n_r\}$;
- A^r Set of disaster areas in sub-region $r \in R$, $\bigcap_{r\in R} A^r = \emptyset$;
- A Set of all disaster areas, $A = \bigcup_{r\in R} A^r$;
- $\mathcal{D}_o^r$ Set of existing sites that have distribution centers but are not allowed to have medical facilities in sub-region $r \in \mathcal{R}$, $\bigcap_{r\in R} \mathcal{D}_o^r = \emptyset$;
- $\mathcal{D}_o$ Set of all existing sites that have distribution centers but are not allowed to have medical facilities, $\mathcal{D}_o = \bigcup_{r\in R} \mathcal{D}_o^r$;
- $\mathcal{M}_o$ Set of existing sites that have medical facilities but are not allowed to have distribution centers;
- $\mathcal{P}_d^r$ Set of candidate sites for temporary distribution centers in sub-region $r \in R$, $\bigcap_{r\in R} \mathcal{P}_d^r = \emptyset$;
- $\mathcal{P}_d$ Set of candidate sites for temporary distribution centers, $\mathcal{P}_d = \bigcup_{r\in R} \mathcal{P}_d^r$;
- $\mathcal{P}_m$ Set of candidate sites for temporary medical facilities;
- α_d^r Set of all sites that either have existing distribution centers or are candidates to have distribution centers in sub-region r, $\alpha_d^r = \mathcal{D}_o^r \cup \mathcal{P}_d^r$, $\mathcal{D}_o^r \cap \mathcal{P}_d^r = \emptyset$;
- α_d Set of all sites that either have existing distribution centers or are candidates to have distribution centers, $\alpha_d = \mathcal{D}_o \cup \mathcal{P}_d$, $\mathcal{D}_o \cap \mathcal{P}_d = \emptyset$;
- α_m Set of all sites that either have existing medical facilities or are candidates to have medical facilities, $\alpha_m = \mathcal{M}_o \cup \mathcal{P}_m$, $\mathcal{M}_o \cap \mathcal{P}_m = \emptyset$;
- T Set of time points, $T = \{0,1,2,\dots,n_t\}$;
- F_0^{in} Set of temporary medical facilities arriving at time point 0 of model implementation;

The following are parameters used in model I and model I_full.

- t_{ik} Estimated travel time (including loading-unloading time) from disaster area i to site k;
- t_{jk} Estimated travel time from site j to site k;
- H_i Estimated total number of injury-free victims in disaster area i (in number of people);
- $W0_i$ Un-evacuated injured victims in disaster area $i$at the beginning of model implementation (in number of people);
- g^1 Total amount of repeatedly-needed-commodity relief (or type-1-commodity relief) needed per time unit per person (in volume unit per person per time unit);
- g^2 Total amount of once-and-for-all-commodity relief (or type-2-commodity relief) needed per person during planning horizon (in volume unit per person);
- $I0_i^1$ Inventory level of type-1-commodity relief in disaster area i at the beginning of model implementation (in volume unit);
- $G0_{ik}^2$ Total amount of type-2-commodity relief already sent from site k to disaster area i up to the beginning of model implementation (in volume unit);
- p_g^1 Penalty for unmet type-1-commodity relief demand of a victim during a particular time period;

p_g^2 Penalty for unmet type-2-commodity relief demand of a victim during a particular time period;
p_h Penalty for an un-evacuated injured victim during a particular time period;
f_{gh} Conversion factor (in volume unit per person);
$Z0_k^{all}$ Number of vehicles already available at site k at the beginning of model implementation;
Cap Capacity of each vehicle (in volume unit);
D Time availability in one time period (in time unit);
M A very big positive number;
N_{dc}^r Maximum number of temporary distribution centers that could be established in sub-region r;
N_{dc} Maximum number of temporary distribution centers that could be established in region R;
V_g^{rin} Number of new vehicles for commodity relief distribution becoming available at the beginning of model implementation in sub-region r;
V_g^{rout} Number of vehicles for commodity relief distribution leaving sub-region r at the beginning of model implementation;
V_h^{in} Number of new vehicles becoming available for victim evacuation at the beginning of model implementation;
V_h^{out} Number of vehicles for victim evacuation leaving the disaster scene at the beginning of model implementation;

Decision variables used in model I or model I_full are defined below.

XX Maximum amongst the weighted unmet commodity relief demands in disaster areas in $A^r, r \in R$ during the planning horizon;
XY Maximum amongst the weighted numbers of un-evacuated injured victims in disaster areas in A during the planning horizon;
YY Maximum amongst the weighted unmet commodity relief demands in disaster areas in A during the planning horizon;
S_{it}^1 Type-1-commodity relief shortages in disaster area i at time point t (in volume unit);
S_{it}^2 Type-2-commodity relief shortages in disaster area i at time point t (in volume unit);
W_{it} Number of un-evacuated injured victims in disaster area i at time point t;
E_{ikt} Number of injured victims evacuated from area i to site k in the period from time point t to $t+1$;
I_{it}^1 Inventory level of type-1-commodity relief in disaster area i at time point t;
G_{ikt}^1 Total amount of type-1-commodity relief sent from site k to disaster area i in the period from time point t to t + 1 (in volume unit);
G_{ikt}^2 Total amount of type-2-commodity relief sent from site k to disaster area i in the period from time point t to t + 1 (in volume unit);

$$U_{jk} = \begin{cases} 1, \text{if medical facility } j \text{ is located to temporary site } k \\ 0, \text{otherwise} \end{cases}, \forall j \in F_0^{in};$$

$$Q_k^{open} = \begin{cases} 1, \text{if site} k \text{ is open} \\ 0, \text{otherwise} \end{cases};$$

$$U_k = \begin{cases} 1, \text{if temporary distribution center is located to site } k \\ 0, \text{ otherwise} \end{cases};$$

$$Y_{ikt} = \begin{cases} 1, \text{if goods needed in area } i \text{ are sent from site } k \\ \quad \text{in the period from } t \text{ to } t+1 \\ 0, \text{otherwise} \end{cases};$$

$$X_{ikt} = \begin{cases} 1, \text{if injured victims in area } i \text{ are transported to site } k \\ \quad \text{in the period from time point } t \text{ to } t+1 \\ 0, \text{otherwise} \end{cases};$$

Z_{kt}^{all} Number of vehicles at site k from period t to $t+1$;
Z_{jkt}^{move} Number of vehicles already available at site j moved from site j to site k at time point t;
Z_k^{new} Number of new vehicles arriving at the beginning of model implementation assigned to site k;
Z_k^{leave} Number of vehicles leaving site k at the beginning of model implementation;
D_{ikt} Vehicle-time allocated/required for making trips between area i and site k in the period from time point t to $t+1$;

In line with the policy in the district, both of the models try to minimize victim suffering due to commodity relief shortage and evacuation delay in the worst disaster areas. Minimizing total suffering over all disaster areas is also considered as a secondary objective.

A. Model I

Model I is available in [6]. The model tries to represent the commodity relief distribution and the victim evacuation practice that took place in a region. Sub-model Ia is devoted to the commodity relief distribution and applies to a certain sub-region only, whereas the victim evacuation process is represented by sub-model Ib and is applicable to the whole region.

1. Sub-Model Ia

In model I, the commodity relief distributions in different sub-regions are performed independently. Model Ia therefore applies to each sub-region *r*.

Objective function:

$$Min\left(|A^r| * XX + \sum_{i\in A^r}\sum_{t=1}^{n_t}\left(p_g^1 * S_{it}^1 + p_g^2 * t * S_{it}^2\right)\right) \quad (1)$$

The objective is to minimize a weighted sum of the maximum suffering due to the commodity relief shortage in the areas and the total suffering due to the commodity relief shortage over all areas in the sub-region, wherein the first term of the objective function is of primary concern. The maximum is provided by constraints (2).

Subject to the following constraints:

Constraints on un-met commodity relief demands:

$$\sum_{t=1}^{n_t}\left(p_g^1 * S_{it}^1 + p_g^2 * t * S_{it}^2\right) \le XX, \forall i \in A^r \quad (2)$$

Variable values at the first time point wherein constraints (4) only apply to the first implementation of the model:

$$I_{i0}^1 = I0_i^1, \forall i \in A^r \quad (3)$$

$$Z_{jk0}^{move} = 0, \forall j \in \alpha_d^r, k \in \alpha_d^r \quad (4)$$

Constraints on commodity relief demands:

$$g^1 * (W_{it} + H_i) - I_{i,t-1}^1 - \sum_{k\in\alpha_d^r} G_{ik,t-1}^1 = S_{it}^1 - I_{it}^1, \forall i \in A^r, t \in T\setminus\{0\} \quad (5)$$

$$g^2 * \left(W_{it} + H_i\right) - \sum_{k\in\mathcal{D}_o^r} G0_{ik}^2 - \sum_{k\in\alpha_d^r}\sum_{\tau=0}^{t-1} G_{ik\tau}^2 \le S_{it}^2, \forall i \in A^r, t \in T\setminus\{0\} \quad (6)$$

$$2 * t_{ik} * (G_{ikt}^1 + G_{ikt}^2)/Cap \le D_{ikt} + M * (1 - Y_{ikt}), \forall i \in A^r, k \in \alpha_d^r, t \in T\setminus\{n_t\} \quad (7)$$

$$G_{ikt}^1 + G_{ikt}^2 - M * Y_{ikt} \le 0, \forall i \in A^r, k \in \alpha_d^r, t \in T\setminus\{n_t\} \quad (8)$$

Constraint on location of provisional sites that applies to the first model implementation only:

$$\sum_{k\in\mathcal{P}_d^r} U_k \le N_{dc}^r \quad (9)$$

Constraints on allocation of disaster areas to sites, wherein constraints (10) do not apply to subsequent implementations of the models:

$$\sum_{i\in A^r} Y_{ikt} \le M * U_k, \forall k \in \mathcal{P}_d^r, t \in T\setminus\{n_t\} \quad (10)$$

$$\sum_{k\in\alpha_d^r} Y_{ikt} = 1, \forall i \in A^r, t \in T\setminus\{n_t\} \quad (11)$$

Constraints on vehicle-time requirement in a particular site wherein there are no vehicles moving in from other sites in the first implementation of the model:

$$\sum_{i\in A^r} D_{ikt} \le D * Z_{kt}^{all} - \sum_{j\in\alpha_d^r}(t_{jk} * Z_{jkt}^{move}), \forall k \in \alpha_d^r, t \in T\setminus\{n_t\} \quad (12)$$

Vehicle availability wherein there are no vehicles moving in from other sites at that time at time point 0:

$$Z0_k^{all} + Z_k^{new} - Z_k^{leave} + \sum_{j\in\alpha_d^r} Z_{jk0}^{move} - \sum_{j\in\alpha_d^r} Z_{kj0}^{move} = Z_{k0}^{all}, \forall k \in \alpha_d^r \quad (13)$$

$$Z_{k,t-1}^{all} + \sum_{j\in\alpha_d^r} Z_{jkt}^{move} - \sum_{j\in\alpha_d^r} Z_{kjt}^{move} = Z_{kt}^{all}, \forall k \in \alpha_d^r, t \in T\setminus\{0, n_t\} \quad (14)$$

Vehicle out-movement:

$$\sum_{k\in\alpha_d^r} Z_{jkt}^{move} = Z_{j,t-1}^{all}, \forall j \in \alpha_d^r, t \in T\setminus\{0, n_t\} \quad (15)$$

Number of vehicles arriving and assigned to a particular site:

$$\sum_{k\in\alpha_d^r} Z_k^{new} = V_g^{rin} \quad (16)$$

Number of vehicles leaving from a particular site:

$$\sum_{k\in\alpha_d^r} Z_k^{leave} = V_g^{rout} \quad (17)$$

Vehicles for commodity relief distribution leaving a site:

$$Z_k^{leave} \le Z0_k^{all}, \forall k \in \alpha_d^r \quad (18)$$

Relation between vehicle deployment and existence of site at the first implementation of the models:

$$Z_{kt}^{all} - M * U_k \leq 0 , \forall k \in \mathcal{P}_d^r, t \in T\backslash\{n_t\} \quad (19)$$

Non-negative variables:

$$XX \geq 0 \quad (20)$$

$$S_{it}^1 \geq 0, \forall i \in A^r, t \in T\backslash\{0\} \quad (21)$$

$$S_{it}^2 \geq 0, \forall i \in A^r, t \in T\backslash\{0\} \quad (22)$$

$$I_{it}^1 \geq 0 , \forall A^r, t \in T \quad (23)$$

$$G_{ikt}^1 \geq 0, \forall i \in A^r, k \in \alpha_d^r, t \in T\backslash\{n_t\} \quad (24)$$

$$G_{ikt}^2 \geq 0, \forall i \in A^r, k \in \alpha_d^r, t \in T\backslash\{n_t\} \quad (25)$$

$$D_{ikt} \geq 0, \forall i \in A^r, k \in \alpha_d^r, t \in T\backslash\{n_t\} \quad (26)$$

Integer variables:

$$Z_{kt}^{all} \geq 0 \text{ and integer}, \forall k \in \alpha_d^r, t \in T\backslash\{n_t\} \quad (27)$$

$$Z_{jkt}^{move} \geq 0 \text{ and integer}, \forall j \in \alpha_d^r, k \in \alpha_d^r, t \in T\backslash\{n_t\} \quad (28)$$

$$Z_k^{new} \geq 0 \text{ and integer}, \forall k \in \alpha_d^r \quad (29)$$

$$Z_k^{leave} \geq 0 \text{ and integer}, \forall k \in \alpha_d^r \quad (30)$$

Binary variables:

$$Y_{ikt} = 0 \; or \; 1, \forall i \in A^r, k \in \alpha_d^r, t \in T\backslash\{n_t\} \quad (31)$$

$$U_k = 0 \; or \; 1, \forall k \in \mathcal{P}_d^r \quad (32)$$

2. Sub-Model Ib

Objective function:

$$Min \left(|A| * XY + \textstyle\sum_{i \in A} \sum_{t=1}^{n_t} (p_h * t * W_{it})\right) \quad (33)$$

The objective of sub-model Ib is to minimize a weighted sum of the maximum suffering and the total suffering due to the evacuation delay of the injured victims from the disaster areas.

Subject to the following constraints:

Un-evacuated injured victims in the disaster areas:

$$\textstyle\sum_{t=1}^{n_t} p_h * t * W_{it} \leq XY, \forall i \in A \quad (34)$$

Several variable values at the first time point wherein constraints (36) apply only to the first implementation of the model:

$$W_{i0} = W0_i, \forall i \in A \quad (35)$$

$$Z_{jk0}^{move} = 0, \forall j \in \alpha_m, k \in \alpha_m \quad (36)$$

Constraints on victim evacuation:

$$W_{it} = W_{i,t-1} - \textstyle\sum_{k \in \alpha_m} E_{ik,t-1}, \forall i \in A, t \in T\backslash\{0\} \quad (37)$$

$$2 * f_{gh} * t_{ik} * E_{ikt}/Cap \leq D_{ikt} + M * (1 - X_{ikt}), \; \forall i \in A, k \in \alpha_m, t \in T\backslash\{n_t\} \quad (38)$$

$$E_{ikt} - M * X_{ikt} \leq 0, \forall i \in A, k \in \alpha_m, t \in T\backslash\{n_t\} \quad (39)$$

Deployment of temporary medical facilities to sites:

$$\textstyle\sum_{k \in \mathcal{P}_m} U_{jk} \leq 1, \forall j \in F_0^{in} \quad (40)$$

Location of provisional sites:

$$Q_k^{open} \leq \textstyle\sum_{j \in F_0^{in}} U_{jk}, \forall k \in \mathcal{P}_m \quad (41)$$

$$M * Q_k^{open} \geq \textstyle\sum_{j \in F_0^{in}} U_{jk}, \forall k \in \mathcal{P}_m \quad (42)$$

Allocation of disaster areas to sites:

$$\textstyle\sum_{i \in A} X_{ikt} \leq M * Q_k^{open}, \forall k \in \mathcal{P}_m, t \in T\backslash\{n_t\} \quad (43)$$

$$\textstyle\sum_{k \in \alpha_m} X_{ikt} = 1 , \forall i \in A, t \in T\backslash\{n_t\} \quad (44)$$

Constraints on vehicle-time requirement in a particular site wherein there are no vehicles moving in from other sites at the first implementation of the model:

$$\textstyle\sum_{i \in A} D_{ikt} \leq D * Z_{kt}^{all} - \textstyle\sum_{j \in \alpha_m} (t_{jk} * Z_{jkt}^{move}), \forall k \in \alpha_m, \; t \in T\backslash\{n_t\} \quad (45)$$

Vehicle availability for victim evacuation:

$$Z0_k^{all} + Z_k^{new} - Z_k^{leave} + \textstyle\sum_{j \in \alpha_m} Z_{jk0}^{move} - \textstyle\sum_{j \in \alpha_m} Z_{kj0}^{move} = Z_{k0}^{all}, \forall k \in \alpha_m \quad (46)$$

$$Z_{k,t-1}^{all} + \textstyle\sum_{j \in \alpha_m} Z_{jkt}^{move} - \textstyle\sum_{j \in \alpha_m} Z_{kjt}^{move} = Z_{kt}^{all}, \forall k \in \alpha_m, t \in T\backslash\{0, n_t\} \quad (47)$$

Vehicle out-movement:

$$\sum_{k\in\alpha_m} Z_{jkt}^{move} = Z_{j,t-1}^{all}, \forall j \in \alpha_m,\ t \in T\backslash\{0, n_t\} \tag{48}$$

Number of vehicles arriving and assigned to a site:

$$\sum_{k\in\alpha_m} Z_k^{new} = V_h^{in} \tag{49}$$

Number of vehicles leaving a site:

$$\sum_{k\in\alpha_m} Z_k^{leave} = V_h^{out} \tag{50}$$

Vehicles leaving from a particular site:

$$Z_k^{leave} \leq Z0_k^{all}, \forall\ k \in \alpha_m \tag{51}$$

Relation between vehicle deployment and existence of site:

$$Z_{kt}^{all} - M * U_k^{open} \leq 0\ , \forall k \in \mathcal{P}_m, t \in T\backslash\{n_t\} \tag{52}$$

Non-negative variables:

$$XY \geq 0 \tag{53}$$

$$W_{it} \geq 0, \forall i \in A, t \in T \tag{54}$$

$$E_{ikt} \geq 0, \forall i \in A, k \in \alpha_m, t \in T\backslash\{n_t\} \tag{55}$$

$$D_{ikt} \geq 0, \forall i \in A, k \in \alpha_m, t \in T\backslash\{n_t\} \tag{56}$$

Integer variables:

$$Z_{kt}^{all} \geq 0 \text{ and integer}, \forall k \in \alpha_m, t \in T\backslash\{n_t\} \tag{57}$$

$$Z_{jkt}^{move} \geq 0 \text{ and integer}, \forall j \in \alpha_m, k \in \alpha_m, t \in T\backslash\{n_t\} \tag{58}$$

$$Z_k^{new} \geq 0 \text{ and integer}, \forall k \in \alpha_m \tag{59}$$

$$Z_k^{leave} \geq 0 \text{ and integer}, \forall k \in \alpha_m \tag{60}$$

Binary variables:

$$X_{ikt} = 0 \text{ or } 1, \forall i \in A, k \in \alpha_m, t \in T\backslash\{n_t\} \tag{61}$$

$$U_{jk} = 0 \text{ or } 1, \forall j \in F_0^{in}, k \in \mathcal{P}_m \tag{62}$$

$$Q_k^{open} = 0 \text{ or } 1, \forall k \in \mathcal{P}_m \tag{63}$$

B. Model I_Full

Similar to model I, model I_full consists of two sub-models. Sub-model Ia_full deals with the relief distribution for the whole region and is simply a slight modification of sub-model Ia, with the only difference being that the constraints are defined on region-related sets instead of sub-region-related sets. In other words, sub-model Ia_full is essentially model Ia applied to a whole region instead of a certain sub-region. The victim evacuation, in the meantime, is represented by sub-model Ib and, therefore, is not provided again in the subsequent parts of this paper. With the coordination of the Implementing Unit for Disaster Management present in Padang Pariaman District, the boundaries of the sub-districts should not be restrictive for the evacuation and distribution activities. Therefore, in terms of the models, division of a region into sub-regions is not considered in model I_full. As a consequence, demands of commodity relief in a particular disaster area in model I_full can be fulfilled by any site with a distribution center. Injured victims in the area, in the meantime, can be transported to any site with a medical facility.

The removal of the boundaries between sub-regions in model I_full enables the relief distribution to be conducted by using shared resources. That is, vehicles for relief distribution can be used to serve the victims in any disaster areas in the region, and the number of temporary distribution centers to open is drastically reduced from whatever number of sub-regions exists to just 1 distribution center.

What follow are the objective function and constraints of sub-model Ia_full.

Objective function:

$$Min\left(|A| * YY + \sum_{i\in A}\sum_{t=1}^{n_t}\left(p_g^1 * S_{it}^1 + p_g^2 * t * S_{it}^2\right)\right) \tag{64}$$

Similar to sub-model Ia, the objective of this sub-model is to minimize a weighted sum of the maximum suffering and the total suffering due to the commodity relief shortage. Different from sub-model Ia, nonetheless, the objective is related to the whole region instead.

Subject to the following constraints:

$$\sum_{t=1}^{n_t}\left(p_g^1 * S_{it}^1 + p_g^2 * t * S_{it}^2\right) \leq YY, \forall i \in A \tag{65}$$

$$I_{i0}^1 = I0_i^1, \forall i \in A \tag{66}$$

$$Z_{jk0}^{move} = 0, \forall j \in \alpha_d, k \in \alpha_d \tag{67}$$

$$g^1 * (W_{it} + H_i) - I_{i,t-1}^1 - \sum_{k\in\alpha_d} G_{ik,t-1}^1 = S_{it}^1 - I_{it}^1, \forall i \in A, t \in T\backslash\{0\} \tag{68}$$

$g^2 * (W_{it} + H_i) - \sum_{k\in\mathcal{D}_o} G0_{ik}^2 - \sum_{k\in\alpha_d}\sum_{\tau=0}^{t-1} G_{ik\tau}^2 \leq S_{it}^2, \forall i \in A, t \in T\backslash\{0\}$ (69)
$2 * t_{ik} * (G_{ikt}^1 + G_{ikt}^2)/Cap \leq D_{ikt} + M * (1 - Y_{ikt}), \forall i \in A, k \in \alpha_d,\ t \in T\backslash\{n_t\}$ (70)
$G_{ikt}^1 + G_{ikt}^2 - M * Y_{ikt} \leq 0, \forall i \in A, k \in \alpha_d, t \in T\backslash\{n_t\}$ (71)
$\sum_{k\in\mathcal{P}_d} U_k \leq N_{dc}$ (72)
$\sum_{i\in A} Y_{ikt} \leq M * U_k, \forall k \in \mathcal{P}_d, t \in T\backslash\{n_t\}$ (73)
$\sum_{k\in\alpha_d} Y_{ikt} = 1, \forall i \in A, t \in T\backslash\{n_t\}$ (74)
$\sum_{i\in A} D_{ikt} \leq D * Z_{kt}^{all} - \sum_{j\in\alpha_d}(t_{jk} * Z_{jkt}^{move}), \forall k \in \alpha_d,\ t \in T\backslash\{n_t\}$ (75)
$Z0_k^{all} + Z_k^{new} - Z_k^{leave} + \sum_{j\in\alpha_d} Z_{jk0}^{move} - \sum_{j\in\alpha_d} Z_{kj0}^{move} = Z_{k0}^{all}, \forall k \in \alpha_d$ (76)
$Z_{k,t-1}^{all} + \sum_{j\in\alpha_d} Z_{jkt}^{move} - \sum_{j\in\alpha_d} Z_{kjt}^{move} = Z_{kt}^{all}, \forall k \in \alpha_d, t \in T\backslash\{0, n_t\}$ (77)
$\sum_{k\in\alpha_d} Z_{jkt}^{move} = Z_{j,t-1}^{all}, \forall j \in \alpha_d,\ t \in T\backslash\{0, n_t\}$ (78)
$\sum_{k\in\alpha_d} Z_k^{new} = V_g^{in}$ (79)
$\sum_{k\in\alpha_d} Z_k^{leave} = V_g^{out}$ (80)
$Z_k^{leave} \leq Z0_k^{all}, \forall k \in \alpha_d$ (81)
$Z_{kt}^{all} - M * U_k \leq 0, \forall k \in \mathcal{P}_d, t \in T\backslash\{n_t\}$ (82)
$YY \geq 0$ (83)
$S_{it}^1 \geq 0, \forall i \in A, t \in T\backslash\{0\}$ (84)
$S_{it}^2 \geq 0, \forall i \in A, t \in T\backslash\{0\}$ (85)
$I_{it}^1 \geq 0, \forall i \in A, t \in T$ (86)
$G_{ikt}^1 \geq 0, \forall i \in A,\ k \in \alpha_d, t \in T\backslash\{n_t\}$ (87)
$G_{ikt}^2 \geq 0, \forall i \in A,\ k \in \alpha_d, t \in T\backslash\{n_t\}$ (88)
$D_{ikt} \geq 0, \forall i \in A, k \in \alpha_d, t \in T\backslash\{n_t\}$ (89)
$Z_{kt}^{all} \geq 0$ and integer, $\forall k \in \alpha_d, t \in T\backslash\{n_t\}$ (90)
$Z_{kt}^{new} \geq 0$ and integer, $\forall k \in \alpha_d, t \in T\backslash\{n_t\}$ (91)
$Z_k^{leave} \geq 0$ and integer, $\forall k \in \alpha_d$ (92)
$Z_{jkt}^{move} \geq 0$ and integer, $\forall j \in \alpha_d, k \in \alpha_d, t \in T\backslash\{n_t\}$ (93)
$Y_{ikt} = 0\ or\ 1, \forall i \in A, k \in \alpha_d, t \in T\backslash\{n_t\}$ (94)
$U_k = 0\ or\ 1, \forall k \in \mathcal{P}_d$ (95)

Constraints (66)-(82) and (84)-(95) are essentially the same as constraints (3)-(19) and (21)-(32) respectively with the exception that the former constraints are defined on region-related sets instead of sub-region-related sets.

A total of 60 computational experiments (30 experiments for each model) were carried out to test the applicability and performance of the models. In doing so, several factors, parameter values and sets were taken into account. A total of 15time points were taken into account. A total of 17 sub-districts and 47 nagaris in the district were also taken into account in the experiments, in which the total number of nagaris was used as the total number of disaster areas. According to the census performed in 2009, the total population of Padang Pariaman District in the year 2008 was 390,247 people. This population was also taken into account. Detailed explanation about the factors, parameter values and sets as well as the control parameter setting in optimization software used is available in [6].

During the process of solving each problem instance, total suffering of the victims due to commodity relief shortage and evacuation delay up to each decision time point (in volume unit) was calculated. Accumulated value of total sufferings at the end of the 15 time periods (in volume unit) is the sum of the total sufferings up to each decision point over the 15 time periods. This value is subsequently used as an indicator of the disaster response effectiveness.

III. Results of Computational Experiments and Discussion

The accumulated values of total sufferings resulted from the computational experiments are provided in Table 1. The table also provides effect size and suffering reductions – both of which are explained below – and differences of the accumulated total sufferings in each experiment.

The computational experiments intended to gain insight into the performance of the models. In order to achieve this insight, this paper addresses the usefulness of the research results (for a discussion of why the usefulness of the research results should be examined, see e.g. [7]). With this motivation, effect size (or ES in short) of the experiments is calculated and the context of the study is taken into account.

TABLE 1. Accumulated Total Sufferings over 15 Time Periods

Experiment	**Accumulated total sufferings**		**Difference**	**Suffering reduction**
	Model I	**Model I_full**		
1	124,782,854.283538	52,501,393.801752	72,281,460.481786	226,054
2	77,654,559.108209	30,813,109.632282	46,841,449.475927	235,398
3	65,903,383.827224	44,067,555.889585	21,835,827.937639	129,301
4	51,525,573.384922	34,992,563.450247	16,533,009.934675	125,219
5	50,747,378.395382	41,886,586.193196	8,860,792.202186	68,139
6	70,775,507.701224	43,791,125.353385	26,984,382.347839	148,788
7	51,827,361.266813	33,317,948.049280	18,509,413.217533	139,371
8	168,157,707.416637	50,657,228.092847	117,500,479.323790	272,686
9	167,370,786.421131	30,441,884.207406	136,928,902.213725	319,268
10	134,243,866.482468	42,017,053.635413	92,226,812.847055	268,103
11	117,222,798.004782	34,360,071.825752	82,862,726.179030	275,859
12	128,328,234.122371	54,675,016.206846	73,653,217.915525	223,980
13	65,725,028.018846	29,220,084.200639	36,504,943.818207	216,751
14	42,264,818.491900	23,328,526.898247	18,936,291.593653	174,846
15	165,279,162.757737	42,151,754.104113	123,127,408.653624	290,721
16	60,970,103.746323	29,334,103.431619	31,636,000.314704	202,490
17	60,450,263.762884	29,873,138.756840	30,577,125.006044	197,396
18	200,960,940.372086	77,706,354.920256	123,254,585.451830	239,349
19	47,686,276.802141	21,895,149.197034	25,791,127.605107	211,065
20	117,031,390.278474	38,130,564.508741	78,900,825.769733	263,099
21	58,322,033.516251	45,448,520.721923	12,873,512.794328	86,140
22	106,109,184.475088	53,550,122.380317	52,559,062.094771	193,301
23	91,757,013.777124	50,664,247.697165	41,092,766.079959	174,770
24	170,850,020.907118	41,217,005.255065	129,633,015.652053	296,101
25	104,563,902.326863	38,214,102.923879	66,349,799.402984	247,627
26	57,929,176.646431	37,663,806.229381	20,265,370.417050	136,520
27	61,967,992.012755	33,153,684.041982	28,814,307.970773	181,460
28	40,815,414.933341	25,485,932.355476	15,329,482.577865	146,569
29	84,754,885.187853	40,874,509.663314	43,880,375.524539	202,044
30	200,170,796.009045	55,001,739.715467	145,169,056.293578	283,017
Average	98,204,947.147899	40,214,496.111315	57,990,451.036584	205,848
ES	1.57			

The ES in the paper is calculated by following [8] on Cohen's effect size d. What follows is Cohen's ES d by using M_E as mean of intervention group, M_C as mean of control group, N as total sample size, SD_E as standard deviation of intervention group and SD_C as standard deviation of control group:

$$d = \frac{M_E - M_C}{\text{Sample SD pooled}} \times \left(\frac{N-3}{N-2.25}\right) \times \sqrt{\frac{N-2}{N}} \tag{96}$$

Where:

$$\text{Sample SD pooled} = \sqrt{\frac{[SD_E{}^2 + SD_C{}^2]}{2}} \tag{97}$$

Because the accumulated total suffering in the paper is of "the smaller the better" type, the implementation of this ES d needs a slight modification. That is, the M_E represents the average of accumulated total sufferings of model I, and the M_C represents the average of accumulated total sufferings of model I_full. The ES d is then calculated using the above formula.

The contextualization of the research is another issue of usefulness of the current research (see, for instance, [9] on contextualization of study). For this reason, a measure referred to as suffering reduction (or SR in short) is calculated. Firstly, relative differences between accumulated total sufferings of relevant models are calculated. Secondly, SR value for each experiment is produced by multiplying the relative differences with the total number of victims in the district as a result of the West Sumatra earthquake.

From Table 1, it is apparent that model I_full outperforms model I. This is clearly indicated by the differences between the accumulated total sufferings, the SR values and the ES of the models.

The differences between the accumulated total sufferings give strong support to the idea that the introduction of model I_full significantly improves the process of distributing the relief and evacuating the victims during the disaster response. The smallest impact (see experiment 5) of model I_full implementation still results in a difference of about one sixth of the accumulated total sufferings of model I. The impact is so significant that the difference is about 82% of the accumulated total sufferings of model I (see experiment 9).

Regarding the SR, it is again evident that the introduction of model I_full dramatically reduces the suffering of the victims. The smallest SR value (see again experiment 5) is 68,139 and is around 17% of the total population of the district in the year 2008. The largest SR value (see again experiment 9) is roughly 82% of the population.

The dominance of model I_full performance over model I is also obvious from the ES value, that is, 1.57. This is much larger than 0.8 and, therefore, is categorized as of large magnitude (see, for example, [8]). This inference is also in line with [7], who proposes that a large ES is associated to a certain treatment of which 89% of the treatment's output exceeds the other treatment's outputs.

From all the indicators mentioned above, it is therefore undeniable that the relief distribution and the victim evacuation during the disaster response can be considerably improved by a resource sharing approach in the sense that the vehicles available for the relief distribution in the district are used to serve the victims in any disaster area and that the temporary distribution centers and related resources are pooled into only 1 temporary distribution center.

The practice found in Padang Pariaman District – that is, the relief distribution and the victim evacuation during disaster response that is conducted in hierarchies – is a common one over all regions in Indonesia. The findings in this paper, however, show that reducing the hierarchies and carrying out the two activities (i.e. relief distribution and victim evacuation) by using resource sharing approach is justifiable and even advisable.

IV. Conclusion

This paper demonstrates that, when carrying out relief distribution and victim evacuation during disaster response, aid providers can boost the effectiveness of their activities by using relief distribution vehicles to serve victims in any disaster area within a certain region and by reducing the number of temporary distribution centers. In other words, effectiveness of relief distribution and victim evacuation can be improved by sharing the resources available at the time being.

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BIOGRAPHY

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