Resource Location for Relief Distribution and Victim Evacuation after a Sudden-Onset Disaster

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Abstract:

Quick responses to sudden-onset disasters and the effective allocation of rescue and relief resources are vital for saving lives and reducing the suffering of the victims. This paper deals with the problem of positioning medical and relief distribution facilities after a sudden-onset disaster event. The background of this study is the situation in Padang Pariaman District after the West Sumatra earthquake. Three models are built for the resource location and deployment decisions. The first model reflects current practice where relief distribution and victim evacuation are performed separately and relief is distributed by distribution centers within administrative boundaries. The second model allows relief to be distributed across boundaries by any distribution center. The third model further breaks down functional barriers to allow the evacuation and relief distribution operations share vehicles. These models are solved directly for small problems and by using a direct approach as well as heuristics for large problems. Test results on small problems show that resource sharing measures, both across boundaries and across different functions, improve on current practice. For large problems, the results give similar conclusions to those for small problems when each model is solved using its own best approach.

Keywords: Humanitarian logistics, Location-allocation, Cross functional coordination, Integer programming, Heuristics

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1. Introduction

Natural disasters kill thousands of people, affect millions of others and cause huge economic damage every year. Furthermore, the frequency of disasters has shown an increasing trend in recent decades. Natural disasters were classified into slow onset disasters and sudden onset disasters by Van Wassenhove (2006). An earthquake is a typical example of a sudden-onset disaster which happens suddenly and is difficult to predict. A strong earthquake could cause damage to areas over a hundred kilometers away from the epicenter, and the emergency disaster response period could last for two weeks. This paper studies a logistics decision problem for victim evacuation and relief distribution in response to this type of disaster. In the remainder of the paper, we simply use disaster to refer to this type of disaster.

To reduce loss of life and the suffering of survivors, any disaster needs to be quickly responded to with on-site actions such as establishing temporary shelters and/or temporary medical facilities, evacuating victims, and distributing relief goods to the victims. Resources for the response to a disaster are often limited, and so it is common that a variety of organizations from different places become involved in the operations. This increases the complexity of management and calls for good coordination (Balcik *et al.*, 2010; Coppola, 2007; Nolte *et al.*, 2012). Different parties may be involved at different time periods (Norio *et al.*, 2012), meaning that resources for disaster response are not always available at the same time points. These resources include vehicles (e.g., Pedraza Martinez *et al.*, 2011; Jotshi *et al.*, 2009) and temporary medical facilities (e.g., Abolghasemi *et al.*, 2006; Merin *et al.*, 2010). For an effective response to a disaster, information on resource availability is crucial. This information is dynamic in nature.

In this study, we consider the logistics decision problem in the emergency response phase with dynamic information on resource availability. The decisions in the problem include determining the locations of temporary medical facilities and relief distribution centers as well as deploying vehicles for carrying out relief distribution and victim evacuation operations. Temporary medical facilities represent medical teams coming with equipment from outside the disaster region. By modeling the problem under different assumptions, we investigate the benefit of coordination.

Our literature search found little previous work that deals with all three decisions on resource location, relief distribution and victim evacuation in response to a disaster. Sheu and Pan (2014) propose a centralized emergency supply network integrating shelter sub-network, medical sub-network and distribution sub-network. A three-stage design approach is taken. Each stage designs one of the sub-networks using a mathematical programming model. The sub-networks are integrated sequentially with the result of an earlier stage used as input for a later stage. The models do not decide the deployment of transportation resources, but consider flow capacities as given constraints. Yi and Özdamar (2007) propose models to make decisions on vehicle routing and the transportation of different commodities over time. The locations of emergency centers are not explicitly modeled as discrete decisions; rather, all potential temporary sites are considered with variable capacities, the allocation of personnel and other resources are modeled as decisions and these resources may be moved around during the planning horizon. Yi and Kumar (2007) consider the routing and distribution problem with fixed demand and supply locations and develop an ant colony optimization heuristic to solve the problem. Manopiniwes and Irohara (2017) develop stochastic programming models to make pre-disaster decisions on the locations and stock amounts of relief distribution centers, considering also post-disaster relief distribution and victim evacuation decisions in different disaster scenarios with probabilities. A known fleet of identical vehicles is assumed. Uster and Dalal (2017) propose a mixed integer linear programming model for designing emergency preparedness network. The decisions include locations of distribution centers, locations and capacity levels of shelters as well as assignment of evacuee source-to-shelter and shelter-to-distribution center assignments. The model tries to minimize two criteria, the maximum distance traveled by evacuees and the system cost. Moreno *et al*. (2016) study a multiperiod location-transportation problem for relief distribution and propose a method to solve the problem in two stages: location of relief centers and assignment of vehicles in the first stage and decision on distribution plan in the second stage. Vehicle resources are considered known and unchanged during the planning horizon. Najafi, *et al*. (2013) propose a multi-objective model to schedule vehicles for transporting relief commodities and injured people, considering uncertainties. A vehicle may be used to transport commodities or people at different times, but the locations of demand and supply as well as hospitals are all considered to be known in advance. In our problem, however, temporary medical centers have to be located to accommodate the temporary medical teams and their equipment, and once established cannot be easily relocated in the planning horizon. In addition, medical teams may come at different times and the exact arrival time of each team may not be known in advance.

Most other previous research considers one aspect of disaster logistics – victim evacuation or relief distribution. On victim evacuation and treatment, Drezner *et al.* (2006) model a problem of locating casualty collection points considering multiple criteria. Jotshi *et al.* (2009) study a problem of dispatching and routing emergency vehicles to pick up casualties and sending them to hospitals. Jia *et al.* (2007) and Huang *et al.* (2010) consider the characteristics of large-scale emergencies and propose location models to determine the locations of medical services.

For relief distribution, Balcik *et al.* (2008) propose models for generating distribution routes from local distribution centers to demand locations and deploying vehicles on these routes. Li *et al.* (2011) develop a multi-objective optimization model for facility location and relief transportation and propose a genetic algorithm to solve it. Widener and Horner (2011) present an allocation model for distributing aid. Afshar and Haghani (2012) propose an integrated model to determine the locations of temporary facilities, vehicle routes and delivery schedules of relief commodities. Lin *et al.* (2012) take a two-phase approach to locating temporary depots, allocating demand points to the depots and then considering detailed operations for relief distribution. Huang *et al*. (2015) develop an integrated multi-objective optimisation model for efficient distribution and delivery of humanitarian aid from supply locations to demand locations through a transportation network. There has been other research focusing on pre-disaster location of resources to prepare for efficient relief distribution operations considering possible disaster occurrences (e.g., Balcik and Beamon, 2008; Salmeron and Apte, 2010; Rawls and Turnquist, 2012; Kusumastuti *et al.*, 2013).

In this research we include both relief distribution and victim evacuation. In deciding the locations of temporary facilities, we consider the constraint of vehicle resources and allow sharing of vehicles in the two operations. The rest of the paper is organized as follows. Section 2 describes the problem studied and provides the general framework for solving the problem. The models used to locate the temporary facilities and to deploy vehicles are presented in Section 3. Section 4 presents two heuristics for solving the models quickly. Computational experiments comparing the performance of the models are reported in Section 5. Finally, conclusions are given in Section 6.

2. Problem Description and Solution Framework

2.1 Background

The background of this study is the situation in Padang Pariaman District after the West Sumatra earthquake. The situation is typical in Indonesia where earthquakes strike frequently. Our field study reveals that, at different levels, the Indonesian government takes both proactive and reactive measures for disaster management. The main government departments responsible for disaster response are the Ministry of Social Affairs and the Ministry of Health (see also Kusumastuti *et al.*, 2013). As a proactive measure, the Ministry of Social Affairs has built warehouses at the national and provincial level and some at district/municipality levels, whereas the Ministry of Health has set up some Centers for Disaster Management. In each district/municipality, there is usually also a warehouse for medical-related goods. From these facility locations, commodity supplies as well as medical teams are dispatched to disaster areas when a disaster strikes. There are also hospitals and other medical facilities serving as destinations of injured victims in the disaster areas.

When a disaster strikes, existing facilities may have been incapacitated or become only partially functional and so cannot provide service optimally. In most cases, there are additional relief goods and medical teams coming from outside in response to the disaster. It is vitally important to position and deploy resources so as to evacuate victims and distribute relief efficiently. Therefore, reactive measures are also taken. Currently in Indonesia, the operations of victim evacuation and relief distribution are conducted separately by the Ministry of Health and the Ministry of Social Welfare respectively. A National Board for Disaster Management and its derivatives have already been set up in several provinces and municipalities/districts, which are given command authority to coordinate various agencies involved during the response phase after a disaster. How to take advantage of this new establishment to coordinate the two operations is yet to be explored and has motivated our research.

2.2 Problem statement

Based on the practice in Padang Pariaman District after the West Sumatra earthquake, disaster management is carried out at three levels. For model purposes and for consistency, we will use the following terms. The whole district affected by the disaster will be referred to as the *region* which comprises several *sub-regions*. Each sub-region consists of a number of *disaster areas*. Each disaster area is a basic unit which will be treated as a point and so local transportation within a disaster area will not be considered. This three-level structure models the problem in reasonable detail and at the same time keeps the complexity of the model manageable. Figure 1 shows a schematic example of the region, sub-regions and disaster areas.

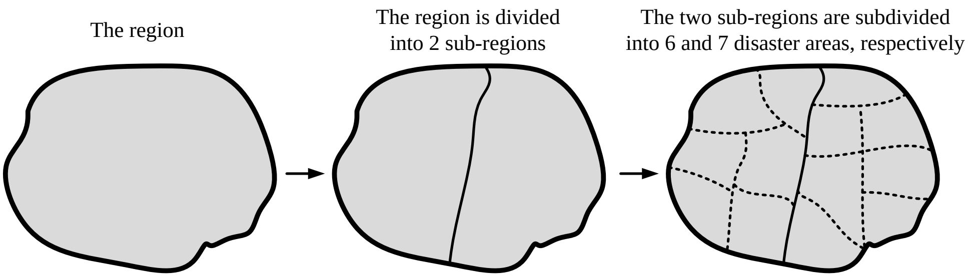

Figure 1 A schematic example of region, sub-regions and disaster areas

Immediately after a disaster happens, information on damage is gathered to guide decisions for disaster relief operations. This known information includes the estimated number of injured victims and the estimated number of injury-free sufferers in each disaster area, distribution centers and hospitals that are still functioning, potential sites that can be used for temporary distribution centers and/or medical centers, available vehicles that can be used for victim evacuation and/or relief distribution, and the estimated travel time between any pair of relevant locations (e.g., existing distribution centers, hospitals, temporary distribution centers, temporary medical centers, and disaster areas), taking into account road damage.

Medical teams with equipment come from other regions or even other countries over time. Each medical team will be sent to a site and will serve as a temporary medical center. More vehicles may also become available over time. Accurate information on these resources will only become available on the day they arrive. While the incoming medical facilities and vehicles may also leave the disaster region at different times, it is sensible to assume that none of them will leave at the same time as they arrive. To make the relief operation possible, it is also sensible to assume that there are at least one distribution center and at least one medical facility in every time period within the planning horizon. A time period here can be taken naturally as one day and the planning horizon is the time span of the emergency response phase, for example two weeks.

Our problem is (a) to determine the locations of temporary distribution centers and temporary medical centers, (b) to allocate each disaster area to a distribution center (existing or temporary) and to a hospital or medical center (existing or temporary), and (c) to deploy vehicles for distributing relief goods to disaster areas from their allocated distribution centers and for evacuating injured victims from the disaster areas to their allocated medical centers (including hospitals). The evacuation may include injury-free victims who need to be evacuated and taken care of. The term “injured victims” will be used to mean all the victims that need to be evacuated. “Injury-free victims” will be used to mean those who do not need to be evacuated from the areas they are. Relief goods need to be distributed to these areas for them use.

Once the location of a temporary center is determined, it will not be changed during the planning horizon, because re-locating a center will waste time and resources and will delay the disaster relief operations. Vehicles for relief distribution and/or for victim evacuation are assumed to use particular sites as bases. All available vehicles can be reallocated at the beginning of each period. Once a vehicle is allocated to a site at the beginning of a time period, it will serve the site during that whole period.

There are two types of relief goods. The demand for Type-1 is reoccurring. Examples of this type include food, medicine and clean water. The demand for Type-2 is one-off in the planning horizon. Examples of this type include tents and clothes. Because of the proactive measures taken before the disaster, supplies of relief goods are sufficient and can be considered as unlimited. If the victims experience a shortage of relief goods, they will suffer. This type of suffering is represented by the unsatisfied relief demand of victims multiplied by the duration over which the demand is not met. Similarly, before injured victims are evacuated, they continue to suffer. This type of suffering is represented by the number of un-evacuated injured victims multiplied by the duration of their waiting for evacuation. The total suffering for an area is the weighted sum of these two types of suffering. The objective of decisions in the problem is to minimize suffering in the worst area as well as the total suffering in all areas.

2.3 Framework of the solution approach

We develop mathematical models to decide the locations of temporary medical centers and temporary relief distribution centers and the allocation of disaster areas and vehicles to these centers. Representing different management policies, three different models are developed. These will be presented in the next section.

We further propose the following approach to make decisions using these models in response to the dynamic arrivals of resources. Any of the above three models can be run in this framework. Immediately after the disaster, the model is run considering the existing facilities and available temporary facilities to be located and the demands and vehicles to be allocated. The decisions will be implemented and operations will be carried out according to the results until the next run of the model. At the beginning of the next period or when new resources become available, the model is run again to plan and modify decisions for operations in the remaining periods using updated information at the time. Temporary facilities located in previous periods are treated as existing ones, and the demands that are already satisfied will not be considered in the subsequent model runs. In each run, the planning horizon of the model is from that time point to the end of the emergency response phase. It is worth emphasizing that the result of each run is only actually implemented for the period until the next run. At the end, the overall performance of a decision model is calculated based on the decisions actually implemented in each period for the whole emergency response phase. Figure 2 illustrates this framework. The approach is implemented in the experiments to test and compare the performance of the models. The experimental results will be presented in Section 5.

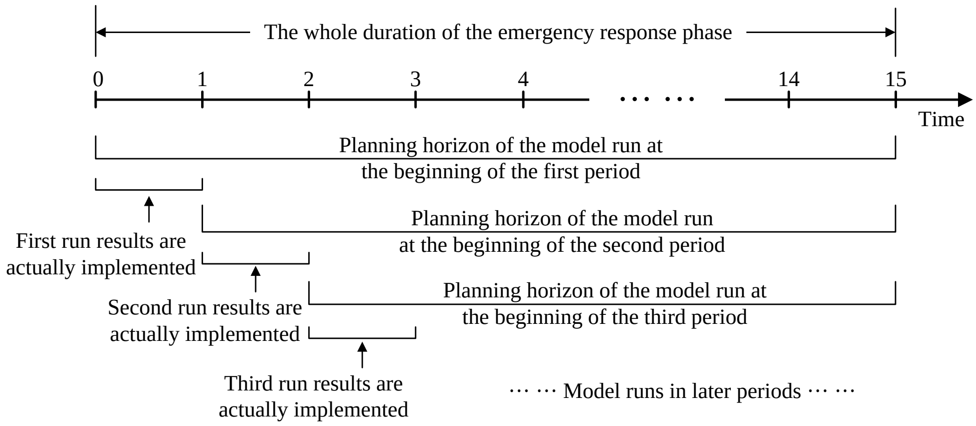

Figure 2 Illustration of model runs in the solution approach

3. The Models

The problem studied here shares a similar structure with a location-allocation problem. However, there are also significant differences. We try to minimize victim suffering in the worst area as well as total suffering over all areas. Therefore, the problem has a mixed feature of *p-center* and *p-median* types. Location-allocation models consider the total demand of each demand point, but do not consider transportation resource constraints and the timings for satisfying demand. In our problem, victim suffering depends on when their demands are satisfied, which is closely related to the availability of transportation resources and the decisions on their deployment. In this section, we present three different models for this problem.

3.1 Model I: The current practice

In the current practice as in the West Sumatra case, relief distribution and victim evacuation are carried out by different government agencies. To reflect this, these two parts can be considered as two sub-systems and modeled separately. Thus model I consists of two sub-models: sub-model Ia for relief distribution and sub-model Ib for victim evacuation. In addition, the current practice allows relief distribution to areas in a sub-region only from a distribution center within the sub-region.

To present the model, we first define the following notation. Some of these will also be used in the other two models later.

Sets and parameters:

R Set of sub-regions in the disaster region, $R = \{1,2,\dots,n_r\}$;

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 with distribution centers in sub-region $r \in \mathcal{R}$, $\bigcap_{r\in R} \mathcal{D}_o^r = \emptyset$;

$\mathcal{M}_o$ Set of existing sites with medical facilities;

Cap_k^m Capacity (number of injured victims can be handled per period) of the medical facility at existing site k, $k \in \mathcal{M}_o$; $Cap_k^m = 0$ for $k \notin \mathcal{M}_o$;

$\mathcal{P}_d^r$ Set of candidate sites for temporary distribution centers in sub-region $r \in R$, $\bigcap_{r\in R} \mathcal{P}_d^r = \emptyset$;

$\mathcal{P}_m$ Set of candidate sites for temporary medical facilities;

α_d^r Set of all sites either with existing distribution centers or candidates for 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_m Set of all sites either with existing medical facilities or candidates for medical facilities, $\alpha_m = \mathcal{M}_o \cup \mathcal{P}_m$, $\mathcal{M}_o \cap \mathcal{P}_m = \emptyset$;

T Set of time points from the current time to the end of the planning horizon, $T = \{0,1,2,\dots,n_t\}$;

F_0^{in} Set of temporary medical facilities arriving at time point 0 of model implementation;

Cap_j^f Capacity (number of injured victims can be handled per period) of temporary medical facility j, $j \in F_0^{in}$; VG Set of vehicle types used for relief distribution in the current practice;

VH Set of vehicle types used for victim evacuation in the current practice;

VA Set of all vehicle types, $VA = VG \cup VH$, $VG \cap VH = \emptyset$;

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 type-1 relief goods needed per time unit per person (in volume unit per person per time unit);

g^2 Total amount of type-2 relief goods needed per person during planning horizon (in volume unit per person);

$I0_i^1$ Inventory level of type-1 relief goods in disaster area i at the beginning of model implementation (in volume unit);

$G0_{ik}^2$ Total amount of type-2 relief goods 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 demand for type-1 relief goods of a victim during a particular time period;

p_g^2 Penalty for unmet demand for type-2 relief goods of a victim during a particular time period;

p_h Penalty for an un-evacuated injured victim during a particular time period;

$Z0_{vk}^{all}$ Number of vehicles of type v already available at site k at the beginning of model implementation;

Cap_v^g Capacity of each vehicle of type v when used for relief distribution (in volume unit);

Cap_v^h Capacity of each vehicle of type v when used for victim evacuation (in number of people);

t_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 to establish in sub-region r;

V_{vg}^{rin} Number of new vehicles of type $v \in VG$ for relief distribution becoming available at the beginning of model implementation in sub-region r;

V_{vg}^{rout} Number of vehicles of type $v \in VG$ for relief distribution leaving sub-region r at the beginning of model implementation;

V_{vh}^{in} Number of new vehicles of type $v \in VH$ becoming available for victim evacuation at the beginning of model implementation;

V_{vh}^{out} Number of vehicles of type $v \in VH$ for victim evacuation leaving the disaster scene at the beginning of model implementation;

Decision variables:

XX Maximum amongst the weighted unmet relief demands in disaster areas in $A^r, r \in R$ during the planning horizon;

XY Maximum among the weighted numbers of un-evacuated injured victims in disaster areas during the planning horizon;

S_{it}^1 Type-1 relief goods shortages in disaster area i at time point t (in volume unit);

S_{it}^2 Type-2 relief goods 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 relief goods in disaster area i at time point t;

G_{ikt}^1 Total amount of type-1 relief goods 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 relief goods sent from site k to disaster area i in the period from time point t to t + 1 (in volume unit);

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

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

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

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

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

Z_{vkt}^{all} Number of vehicles of type v at site k from period t to $t + 1$;

Z_{vjkt}^{move} Number of vehicles of type v already available at site j moved from site j to site k at time point t;

Z_{vk}^{new} Number of new vehicles of type v arriving at the beginning of model implementation assigned to site k;

Z_{vk}^{leave} Number of vehicles of type v leaving site k at the beginning of model implementation;

D_{ikt} *Vehicle resources* (total vehicle capacity-time) allocated/required for making trips between area i and site k in the period from time point t to $t+1$;

Sub-model Ia: Relief distribution

In model I, relief distributions in different sub-regions are performed independently. Therefore, sub-model Ia below is for each sub-region r.

$$\text{Minimize } |A^r| \cdot XX + \sum_{i \in A^r} \sum_{t=1}^{n_t} \left(p_g^1 \cdot S_{it}^1 + p_g^2 \cdot t \cdot S_{it}^2\right) \quad (0)$$

Subject to

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

$$I_{i0}^1 = I0_i^1, \forall i \in A^r \quad (2)$$

$$Z_{vjk0}^{move} = 0, \forall j \in \alpha_d^r, k \in \alpha_d^r, v \in VG \quad (3)$$

$$g^1 \cdot (W_{it} + H_i) - I_{i,t-1}^1 - \sum_{k \in \alpha_d^r} G_{ik,t-1}^1 = S_{it}^1 - I_{it}^1, \forall i \in A^r, t \in T \backslash \{0\} \quad (4)$$

$$g^2 \cdot (W_{it} + H_i) - \sum_{k \in \mathcal{D}_o^r} G0_{ik}^2 - \sum_{k \in \alpha_d^r} \sum_{\tau=0}^{t-1} G_{ik\tau}^2 \leq S_{it}^2, \forall i \in A^r, t \in T \backslash \{0\} \quad (5)$$

$$2 \cdot t_{ik} \cdot (G_{ikt}^1 + G_{ikt}^2) \leq D_{ikt} + M \cdot (1 - Y_{ikt}), \forall i \in A^r, k \in \alpha_d^r, \ t \in T \backslash \{n_t\} \quad (6)$$

$$G_{ikt}^1 + G_{ikt}^2 - M \cdot Y_{ikt} \leq 0, \forall i \in A^r, k \in \alpha_d^r, t \in T \backslash \{n_t\} \quad (7)$$

$$\sum_{k \in \mathcal{P}_d^r} U_k \leq N_{dc}^r \quad (8)$$

$$\sum_{i \in A^r} Y_{ikt} \leq M * U_k, \forall k \in \mathcal{P}_d^r, t \in T \backslash \{n_t\} \quad (9)$$

$$\sum_{k \in \alpha_d^r} Y_{ikt} = 1 \ , \forall i \in A^r, t \in T \backslash \{n_t\} \quad (10)$$

$$\sum_{i \in A^r} D_{ikt} \leq \sum_{v \in VG} (t_D \cdot Cap_v^g \cdot Z_{vkt}^{all}) - \sum_{j \in \alpha_d^r} \sum_{v \in VG} (t_{jk} \cdot Cap_v^g \cdot Z_{vjkt}^{move}) \ , \quad \forall k \in \alpha_d^r, \ t \in T \backslash \{n_t\} \quad (11)$$

$$Z0_{vk}^{all} + Z_{vk}^{new} - Z_{vk}^{leave} + \sum_{j \in \alpha_d^r} Z_{vjk0}^{move} - \sum_{j \in \alpha_d^r} Z_{vkj0}^{move} = Z_{vk0}^{all}, \forall \ k \in \alpha_d^r, v \in VG \quad (12)$$

$$Z_{vk,t-1}^{all} + \sum_{j \in \alpha_d^r} Z_{vjkt}^{move} - \sum_{j \in \alpha_d^r} Z_{vkjt}^{move} = Z_{vkt}^{all}, \forall \ k \in \alpha_d^r, t \in T \backslash \{0, n_t\}, v \in VG \quad (13)$$

$$\sum_{k \in \alpha_d^r} Z_{vjkt}^{move} = Z_{vj,t-1}^{all}, \forall j \in \alpha_d^r, \ t \in T \backslash \{0, n_t\}, v \in VG \quad (14)$$

$$\sum_{k \in \alpha_d^r} Z_{vk}^{new} = V_{vg}^{rin}, v \in VG \quad (15)$$

$$\sum_{k \in \alpha_d^r} Z_{vk}^{leave} = V_{vg}^{rout}, v \in VG \quad (16)$$

$$Z_{vk}^{leave} \leq Z0_{vk}^{all}, \forall \ k \in \alpha_d^r, v \in VG \quad (17)$$

$$\sum_{v \in VG} Z_{vkt}^{all} - M \cdot U_k \leq 0 \ , \forall k \in \mathcal{P}_d^r, t \in T \backslash \{n_t\} \quad (18)$$

$$XX \geq 0 \quad (19)$$

$$S_{it}^1,\ S_{it}^2,\ I_{it}^1 \geq 0, \forall i \in A^r, t \in T\backslash\{0\} \tag{20}$$

$$G_{ikt}^1, G_{ikt}^2,\ D_{ikt} \geq 0, \forall\ i \in A^r, k \in \alpha_d^r, t \in T\backslash\{n_t\} \tag{21}$$

$$Z_{vkt}^{all},\ Z_{vjkt}^{move},\ Z_{vk}^{new},\ Z_{vk}^{leave} \geq 0 \text{ and integer}, \forall j \in \alpha_d^r, \forall k \in \alpha_d^r, t \in T\backslash\{n_t\}, v \in VG \tag{22}$$

$$Y_{ikt} = 0\ or\ 1, \forall i \in A^r, k \in \alpha_d^r,\ t \in T\backslash\{n_t\} \tag{23}$$

$$U_k = 0\ or\ 1, \forall k \in \mathcal{P}_d^r \tag{24}$$

Objective function (0) is related to the weighted amount of unmet demand for relief goods in each disaster area in the sub-region over the planning horizon. While this quantity may be different for different areas, the objective is to minimize a weighted sum of the maximum among the quantities in the areas and the total quantity in the whole sub-region. The maximum is provided by constraints (1). In order to prioritize the minimization of the first term, a large weight is set for this term. The two terms represent the maximum and total victim suffering, respectively, due to the relief shortage. As can be seen in constraints (1), un-met demands for relief goods are weighted with penalty values. The demand for type-1 goods are reoccurring. Each delivery may be enough for a few days. Shortage of this type of goods on a day tends to appear only after the inventory is used up, and so related suffering tends to be short term. The demand for type-2 goods are one-off. Any shortage on a day means that the suffering has been accumulating since the disaster happened. Therefore, the penalty for the un-met demand for type-2 goods is set to increase -with *t*. This will force the demand for type-2 goods to be fulfilled as soon as possible. Constraints (2) define the initial inventory level of type-1 goods. Constraints (3) relate to vehicle movement at the first time point of the first implementation of the model. This set of constraints does not apply in subsequent runs of the model in later time periods.

Constraints (4) determine the amount of the shortage or inventory of type-1 relief goods in each disaster area at the end of each period. If the demand in the period is greater than or equal to the supply including the inventory at the beginning of the period and the amount distributed to the area during the period, then the difference will be the shortage and there will be no inventory at the end of the period. Otherwise, there will be some inventory left and no shortage. The shortage of type-2 relief goods at time point one onwards, on the other hand, cannot be less than the amount of commodities required by un-evacuated injured victims and injury-free victims at the time point minus the total amount of the supplied goods of this type up to the point. Constraints (5) reflect this relation.

Constraints (6) require that the amount of supplied goods from a site to an area in a time period cannot exceed the goods vehicle resources allocated between the two locations during the time period. Constraints (7) ensure that a site can supply goods to a disaster area only if the area is allocated to the site. Constraint (8) relates to the number of temporary sites with distribution centers to open at the beginning of the first implementation of the model. In this case, the total number of sites with distribution centers to open in a sub-region cannot exceed the maximum number of new distribution centers to establish for the sub-region. The constraints do not apply from the second model implementation onwards. Constraints (9) ensure that a site must be open in order for it to supply relief goods. Because provisional sites with distribution centers are determined only once in the first implementation of the models, constraints (9) do not apply to subsequent implementations of the models. The opened sites will be treated as existing sites in the subsequent implementations. Constraints (10) require that relief demands in an area in a given time period are satisfied by exactly one site.

Constraints (11) state that the vehicle resources at a distribution center during a time period is determined by the resources of all the vehicles at the site in the time period, minus the resources wasted on vehicle moving from other sites to this site at the beginning of the time period. The number of vehicles available for relief distribution at a given site from time point one onwards is determined by three different factors: 1) number of vehicles already available at the site, 2) number of vehicles moving into, and 3) number of vehicles leaving the site at that point. Constraints (13) reflect this situation, while constraints (12) correspond to the number of relief distribution vehicles available at sites at time point 0. When the model is first implemented, there is neither vehicle movement nor leaving vehicles at time point 0. The number of vehicles for relief distribution moving from a site to other sites (including those moving to the site itself, i.e., staying at the site) at the beginning of any particular time period (except the first time period) should be equal to the number of vehicles already available at the site in the previous time period. Constraints (14) reflect this relation.

Constraints (15) require that vehicles arriving and available for relief distribution within a particular sub-region are always deployed to sites. Constraints (16) state that the total number of vehicles for relief distribution leaving all sites with distribution centers in a sub-region at the beginning of any implementation of the model is equal to the number of relief distribution vehicles leaving the sub-region. Constraints (17) ensure that the number of vehicles for relief distribution leaving a site at time point 0 of the model implementation cannot exceed the number of vehicles available at the site at the time point. The constraints are in line with the requirement that no vehicle can arrive at and leave a site at the same time. Constraints (18) require that the relief distribution vehicles are deployed to a particular site only if the site is open, which apply to the first implementation of the models only. Constraints (19) to (24) define the value ranges of the variables.

Sub-model Ib: Victim evacuation

$$\text{Minimize } |A| \cdot XY + \sum_{i \in A} \sum_{t=1}^{n_t} (p_h \cdot t \cdot W_{it}) \tag{25}$$

Subject to

$$\sum_{t=1}^{n_t} p_h \cdot t \cdot W_{it} \leq XY, \forall i \in A \tag{26}$$

$$W_{i0} = W0_i, \forall i \in A \tag{27}$$

$$Z_{jk0}^{move} = 0, \forall j \in \alpha_m, k \in \alpha_m \tag{28}$$

$$W_{it} = W_{i,t-1} - \sum_{k\in\alpha_m} E_{ik,t-1}, \forall i \in A, t \in T\backslash\{0\} \tag{29}$$

$$2 \cdot t_{ik} \cdot E_{ikt} \leq D_{ikt} + M \cdot (1 - X_{ikt}), \ \forall i \in A, k \in \alpha_m, t \in T\backslash\{n_t\} \tag{30}$$

$$E_{ikt} - M \cdot X_{ikt} \leq 0, \forall i \in A, k \in \alpha_m, t \in T\backslash\{n_t\} \tag{31}$$

$$\sum_{k\in\alpha_m} U_{jk} \leq 1, \forall j \in F_0^{in} \tag{32}$$

$$Q_k^{open} \leq \sum_{j\in F_0^{in}} U_{jk}, \forall k \in \mathcal{P}_m \tag{33}$$

$$M \cdot Q_k^{open} \geq \sum_{j\in F_0^{in}} U_{jk}, \forall k \in \mathcal{P}_m \tag{34}$$

$$\sum_{k\in\alpha_m} X_{ikt} = 1, \forall i \in A, t \in T\backslash\{n_t\} \tag{35}$$

$$\sum_{i\in A} X_{ikt} \leq M \cdot Q_k^{open}, \forall k \in \mathcal{P}_m, t \in T\backslash\{n_t\} \tag{36}$$

$$\sum_{i\in A} E_{ikt} \leq \sum_{j\in F_0^{in}} Cap_j^f U_{jk}, \forall k \in P_m, t \in T\backslash\{n_t\} \tag{37}$$

$$\sum_{i\in A} E_{ikt} \leq Cap_k^m + \sum_{j\in F_0^{in}} Cap_j^f U_{jk}, \forall k \in M_o, t \in T\backslash\{n_t\} \tag{38}$$

$$\sum_{i\in A} D_{ikt} \leq \sum_{v\in VH}(t_D \cdot Cap_v^h \cdot Z_{vkt}^{all}) - \sum_{j\in\alpha_m}\sum_{v\in VH}(t_{jk} \cdot Cap_v^h \cdot Z_{vjkt}^{move}), \quad \forall k \in \alpha_m, \ t \in T\backslash\{n_t\} \tag{39}$$

$$Z0_{vk}^{all} + Z_{vk}^{new} - Z_{vk}^{leave} + \sum_{j\in\alpha_m} Z_{vjk0}^{move} - \sum_{j\in\alpha_m} Z_{vkj0}^{move} = Z_{vk0}^{all}, \forall k \in \alpha_m, v \in VH \tag{40}$$

$$Z_{vk,t-1}^{all} + \sum_{j\in\alpha_m} Z_{vjkt}^{move} - \sum_{j\in\alpha_m} Z_{vkjt}^{move} = Z_{vkt}^{all}, \forall k \in \alpha_m, t \in T\backslash\{0, n_t\}, v \in VH \tag{41}$$

$$\sum_{k\in\alpha_m} Z_{vjkt}^{move} = Z_{vj,t-1}^{all}, \forall j \in \alpha_m, \ t \in T\backslash\{0, n_t\}, v \in VH \tag{42}$$

$$\sum_{k\in\alpha_m} Z_{vk}^{new} = V_{vh}^{in}, v \in VH \tag{43}$$

$$\sum_{k\in\alpha_m} Z_{vk}^{leave} = V_{vh}^{out}, v \in VH \tag{44}$$

$$Z_{vk}^{leave} \leq Z0_{vk}^{all}, \forall k \in \alpha_m, v \in VH \tag{45}$$

$$\sum_{v\in VH} Z_{vkt}^{all} - M \cdot U_k^{open} \leq 0, \forall k \in \mathcal{P}_m, t \in T\backslash\{n_t\} \tag{46}$$

$$XY \geq 0, \tag{47}$$

$$W_{it} \geq 0, \forall i \in A, t \in T \tag{48}$$

$$E_{ikt}, \ D_{ikt} \geq 0, \forall i \in A, k \in \alpha_m, t \in T\backslash\{n_t\} \tag{49}$$

$$Z_{vkt}^{all}, \ Z_{vjkt}^{move}, \ Z_{vk}^{new}, \ Z_{vk}^{leave} \geq 0 \text{ and integer}, \forall k \in \alpha_m, j \in \alpha_m, t \in T\backslash\{n_t\}, v \in VH \tag{50}$$

$$X_{ikt} = 0 \text{ or } 1, \forall i \in A, k \in \alpha_m, t \in T\backslash\{n_t\} \tag{51}$$

$$U_{jk} = 0 \text{ or } 1, \forall j \in F_0^{in}, k \in \alpha_m \tag{52}$$

$$Q_k^{open} = 0 \text{ or } 1, \forall k \in \mathcal{P}_m \tag{53}$$

The objective of sub-model Ib is to minimize the weighted sum of the maximum suffering and total suffering of un-evacuated injured victims in disaster areas. Suffering here refers to the delay in evacuation. Again, a larger weight is assigned to the first term to prioritize the minimization of maximum suffering.

Constraints (26) calculate the maximum weighted number among un-evacuated injured victims in disaster areas during the planning horizon (i.e. maximum suffering). The number of un-evacuated injured victims at the first time point is defined in constraints (27). Constraints (28), which only apply to the first implementation of the model, represent vehicle movement at the first time point. Constraints (29) state that the number of un-evacuated victims in an area at a given time point is equal to the number of un-evacuated victims at the previous point minus the number of evacuated victims between these two time points. Constraints (30) calculate the vehicle resource requirement for evacuating victims from an area to a site in a time period based on the number of injured victims evacuated. Constraints (31) require that the number of evacuated victims for any unconnected site-area pair in the sub-models is zero.

Constraints (32) indicate that a temporary medical facility is deployed to at most one temporary site. Constraints (33) and (34) relate to medical facilities arriving at the beginning of the model implementation. In this sense, a provisional site is open for medical services when there is at least one temporary medical facility allocated to it. Constraints (35) require that, in a given time period, injured victims in an area are evacuated to exactly one site, while constraints (36) guarantee that evacuation must be to a site that is open.

Constraints (37) state that the total number of injured victims evacuated to a temporary site in each period must be no more than the total handling capacity of the temporary medical facilities allocated to the site. Constraints (38) are similar capacity constraints for the sites with existing medical facilities. The total handling capacity of such a site is the sum of the capacities of existing facilities at the site and the temporary medical facilities allocated to the site.

Vehicle resource requirement for a site with a medical facility to conduct evacuation during any time period is defined by constraints (39). Similar to constraints (11) of sub-model Ia, the vehicle resource is determined by the resources of all vehicles available at the site in the time period minus the resource wasted on vehicle moving from other sites to this site. Again, a special case appears in the first implementation of the model. That is, there are no vehicles moving in from other sites at that time. Vehicle availability for victim evacuation is defined by constraints (40) and (41). The explanations are similar to those for constraints (12) and (13).

Requirements on leaving vehicles in sub-model Ib are provided by constraints (42). Analogous with constraint (14) of sub-model Ia, the total number of evacuation vehicles moving out of a site to all sites (including those staying at the site) at a given time point (except time point 0 and the last time point) is equal to the number of evacuation vehicles available at the site in the period. Constraint (43) requires that the total number of vehicles for victim evacuation arriving at the beginning of the model implementation and assigned to all sites is exactly equal to the number of available vehicles.

Constraint (44) requires that the total number of vehicles for victim evacuation leaving all sites with medical facilities is exactly the same as the number of victim evacuation vehicles leaving the disaster scene. Constraints (45) ensure that the number of vehicles for victim evacuation leaving a site at the beginning of the model implementation cannot exceed the number of vehicles already available at that time point at that site. Constraints (46) ensure the deployment of evacuation vehicles to a site is carried out only if the site is open. Constraints (47) to (53) define the value ranges of the variables.

3.2 Model I revised: Current practice without sub-region boundaries

Even if relief distribution and victim evacuation operations continue to be carried out separately, the current practice may be improved by allowing relief distribution across the sub-region boundaries, just as the evacuation operation does. With the coordination of the National Board for Disaster Management and its derivatives, this can be achieved easily. We revise model I to represent this improvement. The revised model will be called model I_R.

Model I_R also consists of two sub-models, Ia_R and Ib_R, dealing with relief distribution and victim evacuation, respectively. Compared to model I, sub-model Ib_R is exactly the same as sub-model Ib and so the difference is only in sub-model Ia_R which is presented below. Model Ia_R uses the following new sets and a new variable, some of which will also be used in model II.

$\mathcal{D}_o$ Set of all existing sites with distribution centers, $\mathcal{D}_o = \bigcup_{r\in R} \mathcal{D}_o^r$;

$\mathcal{P}_d$ Set of candidate sites for temporary distribution centers, $\mathcal{P}_d = \bigcup_{r\in R} \mathcal{P}_d^r$;

α_d Set of all sites either with existing distribution centers or candidates for distribution centers, $\alpha_d = \mathcal{D}_o \cup \mathcal{P}_d, \mathcal{D}_o \cap \mathcal{P}_d = \emptyset$;

N_{dc} Maximum number of temporary distribution centers to establish in the whole region;

YY Decision variable defined to represent the maximum among the weighted un-met demands for relief goods in all disaster areas during the planning horizon.

Using these and some notation defined earlier, sub-model Ia_R can be presented as follows.

$$\text{Minimize } |A| \cdot YY + \sum_{i\in A} \sum_{t=1}^{n_t} \left(p_g^1 \cdot S_{it}^1 + p_g^2 \cdot t \cdot S_{it}^2\right) \tag{0\_R}$$

Subject to

Constraints (1_R) to (24_R)

These constraints are similar to constraints (1)-(24), but slightly revised by replacing some sub-region-related sets, parameters and variables with those related to the whole region. Five examples are listed below.

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

$$I_{i0}^1 = I0_i^1, \forall i \in A \quad (2\_R)$$

$$\sum_{k \in \mathcal{P}_d} U_k \leq N_{dc} \quad (8\_R)$$

$$YY \geq 0 \quad (19\_R)$$

$$S_{it}^1,\ S_{it}^2,\ I_{it}^1 \geq 0, \forall i \in A, t \in T \backslash \{0\} \quad (20\_R)$$

Sub-model Ia_R is essentially sub-model Ia applied to a whole region instead of a certain sub-region. Therefore, the objective and constraints of this sub-model have similar meanings to those of sub-model Ia. Though model I_R is not much different from model I, the sharing of relief distribution resources among sub-regions does make an improvement as can be seen from the results comparing the two models presented at a conference (Setiawan, 2016) and those in Section 5.

3.3 Model II: collaborated operation for relief distribution and victim evacuation

To fully utilize the coordination potential of the National Board for Disaster Management and its derivatives, another model, model II, is developed by further allowing each vehicle to be used for both relief distribution and victim evacuation, in addition to the lifting of sub-region boundary restrictions. But as in Najafi, *et al*. (2013), a vehicle will not be used to transport goods and people at the same time. The vehicles normally used for relief distributions are vans or even light trucks which are not ideal for evacuating heavily injured people. However, they can be used to evacuate people with minor injuries and this is better than leaving these victims at the disaster site waiting further for ambulances. Model II is an integrated model, rather than one with two separate parts. With vehicle sharing allowed, apart from vehicles delivering relief from a distribution center to a disaster area and back, and vehicles going from a medical center to a disaster area and returning to the medical center carrying victims, there are also vehicles delivering relief from a distribution center to a disaster area, then evacuating victims from this area to a medical center and then returning to the distribution center for the next trip. Such vehicles will be counted as based at the distribution center. In the integrated model, among all the existing site with medical facilities, $\mathcal{M}_o$, some may be suitable for setting up a distribution center as well. Similarly, among all the existing sites with distribution centers, $\mathcal{D}_o$, some may also be suitable for locating medical facilities. Therefore, after the initial period, some existing sites may have both medical facilities and distribution centers. New sets need to be defined to represent different types of existing sites.

In addition to the notation defined earlier, the following sets and parameters are defined and used in model II.

$\mathcal{D}$ Subset of existing sites with distribution centers that are also suitable to locate medical facilities;

$\mathcal{D}'$ Subset of existing sites with distribution centers that are not suitable to locate medical facilities;

$\mathcal{M}$ Subset of existing sites with medical facilities that are also suitable to locate distribution centers;

$\mathcal{M}'$ Subset of existing sites with medical facilities that are not suitable to locate distribution centers;

$\mathcal{B}$ Set of sites with both distribution centers and medical facilities;

Cap_k^m Capacity (number of injured victims can be handled per period) of all medical facilities at existing site k, $k \in \mathcal{M}_o \cup \mathcal{B}$; $Cap_k^m = 0$ for $k \notin \mathcal{M}_o \cup \mathcal{B}$;

$\mathcal{P}_b$ Set of candidate sites for both temporary distribution centers and temporary medical facilities;

δ_d Set of all potential sites for new distribution centers in model II, $\delta_d = \mathcal{M} \cup \mathcal{P}_d \cup \mathcal{P}_b$, $\mathcal{M}, \mathcal{P}_{d,} \mathcal{P}_b$ are mutually exclusive;

δ_m Set of all potential sites for new medical facilities in model II, $\delta_m = \mathcal{D} \cup \mathcal{P}_m \cup \mathcal{P}_b$, $\mathcal{D}$, $\mathcal{P}_{m,}$ $\mathcal{P}_b$ are mutually exclusive;

β_d Set of all sites either with existing distribution centers or candidates for distribution centers in model II, $\beta_d = \mathcal{D}' \cup \mathcal{D} \cup \mathcal{B} \cup \mathcal{M} \cup \mathcal{P}_d \cup \mathcal{P}_b$, $\mathcal{D}', \mathcal{D}, \mathcal{B}, \mathcal{M}, \mathcal{P}_d, \mathcal{P}_b$ are mutually exclusive;

β_m Set of all sites either with existing medical facilities or candidates for medical facilities in model II, $\beta_m = \mathcal{M}' \cup \mathcal{M} \cup \mathcal{B} \cup \mathcal{D} \cup \mathcal{P}_m \cup \mathcal{P}_b$, $\mathcal{M}', \mathcal{M}, \mathcal{B}, \mathcal{D}, \mathcal{P}_m, \mathcal{P}_b$ are mutually exclusive;

$\mathcal{E}_d$ Set of all sites with existing distribution centers in model II, $\mathcal{E}_d = \mathcal{D}' \cup \mathcal{D} \cup \mathcal{B}$, $\mathcal{D}', \mathcal{D}, \mathcal{B}$ are mutually exclusive;

$\mathcal{L}$ Set of all sites in model II, $\mathcal{L} = \mathcal{D}' \cup \mathcal{D} \cup \mathcal{M}' \cup \mathcal{M} \cup \mathcal{B} \cup \mathcal{P}_d \cup \mathcal{P}_m \cup \mathcal{P}_b$, $\mathcal{D}'\mathcal{D}, \mathcal{M}', \mathcal{M}, \mathcal{B}, \mathcal{P}_d, \mathcal{P}_m, \mathcal{P}_b$ are mutually exclusive;

V_v^{in} Number of new vehicles of type v becoming available at the beginning of model implementation;

V_v^{out} Number of vehicles of type v which leave the disaster scene at the beginning of model implementation.

In addition to some of the variables appearing in models I and I_R, model II also uses the following new decision variables.

ZZ Maximum among the sums of the weighted number of un-evacuated injured victims and the weighted unmet demands for relief goods during the planning horizon;

$\bar{E}_{ikt}$ Number of injured victims evacuated from area i directly to site k in the period from time point t to $t+1$;

$\tilde{E}_{ikt}$ Number of injured victims evacuated from area i to site k by vehicles that are allocated to another site j but going through site k in the period from time point t to $t+1$;

$\bar{G}_{ikt}^1$ Total amount of type-1 relief sent from site k directly to disaster area i in the period from time point t to $t+1$ (in volume unit);

$\tilde{G}_{ikt}^1$ Total amount of type-1 relief sent from site k to disaster area i by vehicles going through site j in the period from time point t to $t+1$ (in volume unit);

$\bar{G}_{ikt}^2$ Total amount of type-2 relief sent from site k directly to disaster area i in the period from time point t to $t+1$ (in volume unit);

$\tilde{G}_{ikt}^2$ Total amount of type-2 relief sent from site k to disaster area i by vehicles going through site j in period from time point t to $t+1$ (in volume unit);

$\bar{D}_{ikt}$ Vehicle resources (total vehicle capacity-time) allocated/required for distributing relief from site k to area i and return empty in the period from time point t to $t+1$;

$\tilde{D}_{ikt}^g$ Vehicle resources (total vehicle capacity-time) required for relief distribution in the journeys distributing relief from site k to area i and then evacuating victims from that area, in the period from time point t to $t+1$;

$\tilde{D}_{ikt}^h$ Vehicle resources (total vehicle capacity-time) required for victim evacuation in the journeys distributing relief from site k to area i and then evacuating victims from that area, in the period from time point t to $t+1$;

$\tilde{Z}_{vkt}^{all}$ Number of vehicles of type v at site k from period t to $t+1$, for journeys distributing relief from site k to an area and then evacuating victims from that area;

$\tilde{Z}_{vjkt}^{move}$ Number of vehicles of type v already available at site j moved from site j to site k at time point t, for journeys distributing relief from site k to an area and then evacuating victims from that area;

Figure 3 illustrates different kinds of vehicle journeys in model II and the associated amounts defined above. Variables $\tilde{Z}^{all}_{vkt}$ and $\tilde{Z}^{move}_{vjkt}$ are related to the kind of trips as shown in solid lines in Figure 3. Such a trip combines relief delivery and victim evacuation. It may consist of three segments as shown in the figure, or two segments in case distribution center *k* and medical facility *j* are located at the same site. For each distribution center, only some vehicles are allocated for such combined trips. There are other vehicles for pure relief distribution trips between the distribution center and an area. A vehicle in a distribution center may be used for combined trips in part of the period and for pure trips in the rest part of the period. Therefore, $\tilde{Z}^{all}_{vkt}$ and $\tilde{Z}^{move}_{vjkt}$ need not to be integer.

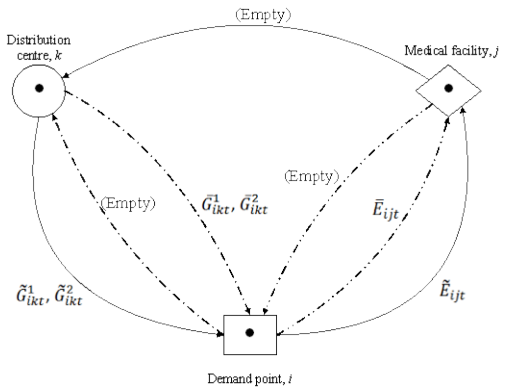

Figure 3 Example of vehicle journeys in model II

Model II is presented below.

$$\text{Minimize } |A| \cdot ZZ + \sum_{i \in A} \sum_{t=1}^{n_t} \left(p_h \cdot t \cdot f_{gh} \cdot W_{it} + p_g^1 \cdot S_{it}^1 + p_g^2 \cdot t \cdot S_{it}^2 \right) \quad (54)$$

Subject to

$$\sum_{t=1}^{n_t} \left(p_h \cdot t \cdot f_{gh} \cdot W_{it} + p_g^1 \cdot S_{it}^1 + p_g^2 \cdot t \cdot S_{it}^2 \right) \leq ZZ, \forall i \in A \quad (55)$$

$$Z^{move}_{vjk0} = 0, \forall j \in \mathcal{L}, k \in \mathcal{L}, v \in VA \quad (56)$$

$$g^1 \cdot (W_{it} + H_i) - I^1_{i,t-1} - \sum_{k \in \beta_d} (\bar{G}^1_{ik,t-1} + \tilde{G}^1_{ik,t-1}) = S^1_{it} - I^1_{it}, \forall i \in A, t \in T \backslash \{0\} \quad (57)$$

$$g^2 \cdot (W_{it} + H_i) - \sum_{k \in \mathcal{E}_d} G0^2_{ik} - \sum_{k \in \beta_d} \sum_{\tau=0}^{t-1} (\bar{G}^2_{ik\tau} + \tilde{G}^2_{ik\tau}) \leq S^2_{it}, \forall i \in A, t \in T \backslash \{0\} \quad (58)$$

$$W_{it} = W_{i,t-1} - \sum_{k \in \beta_m} (\bar{E}_{ik,t-1} + \tilde{E}_{ik,t-1}), \forall i \in A, t \in T \backslash \{0\} \quad (59)$$

$$2 \cdot t_{ik} \cdot \bar{E}_{ikt} \leq D_{ikt} + M \cdot (1 - X_{ikt}), \ \forall i \in A, k \in \beta_m, t \in T \backslash \{n_t\} \quad (60)$$

$$2 \cdot t_{ik} \cdot (\bar{G}^1_{ikt} + \bar{G}^2_{ikt}) \leq \bar{D}_{ikt} + M \cdot (1 - Y_{ikt}), \forall i \in A, k \in \beta_d, t \in T \backslash \{n_t\} \quad (61)$$

$$(t_{ik} + t_{kj} + t_{ji}) \cdot \tilde{E}_{ijt} \leq \tilde{D}^h_{ikt} + M \cdot (2 - Y_{ikt} - X_{ijt}), \forall i \in A, k \in \beta_d, \ j \in \beta_m, t \in T \backslash \{n_t\} \quad (62)$$

$$(t_{ik} + t_{kj} + t_{ji}) \cdot (\tilde{G}^1_{ikt} + \tilde{G}^2_{ikt}) \leq \tilde{D}^g_{ikt} + M \cdot (2 - Y_{ikt} - X_{ijt}), \quad \forall i \in A, k \in \beta_d, \ j \in \beta_m, t \in T \backslash \{n_t\} \quad (63)$$

$$\bar{G}^1_{ikt} + \bar{G}^2_{ikt} + \tilde{G}^1_{ikt} + \tilde{G}^2_{ikt} - M \cdot Y_{ikt} \leq 0, \forall i \in A, k \in \beta_d, t \in T \backslash \{n_t\} \quad (64)$$

$$\bar{E}_{ikt} + \tilde{E}_{ikt} - M \cdot X_{ikt} \le 0, \forall i \in A, k \in \beta_m, t \in T\backslash\{n_t\} \quad (65)$$

$$\sum_{k\in\delta_m} U_{jk} \le 1, \forall j \in F_0^{in} \quad (66)$$

$$Q_k^{open} \le \sum_{j\in F_0^{in}} U_{jk}, \forall k \in \delta_m \quad (67)$$

$$M \cdot Q_k^{open} \ge \sum_{j\in F_0^{in}} U_{jk}, \forall k \in \delta_m \quad (68)$$

$$\sum_{k\in\delta_d} U_k \le N_{dc} \quad (69)$$

$$\sum_{i\in A} Y_{ikt} \le M \cdot U_k, \forall k \in \delta_d, t \in T\backslash\{n_t\} \quad (70)$$

$$\sum_{k\in\beta_d} Y_{ikt} = 1, \forall i \in A, t \in T\backslash\{n_t\} \quad (71)$$

$$\sum_{i\in A} X_{ikt} \le M \cdot Q_k^{open}, \forall k \in \delta_m, t \in T\backslash\{n_t\} \quad (72)$$

$$\sum_{k\in\beta_m} X_{ikt} = 1, \forall i \in A, t \in T\backslash\{n_t\} \quad (73)$$

$$\sum_{i\in A}(E_{ikt} + \tilde{E}_{ikt}) \le \sum_{j\in F_0^{in}} Cap_j^f U_{jk}, \forall k \in \beta_m\backslash(\mathcal{M}_o \cup \mathcal{B}) \quad (74)$$

$$\sum_{i\in A}(E_{ikt} + \tilde{E}_{ikt}) \le Cap_k^m + \sum_{j\in F_0^{in}} Cap_j^f U_{jk}, \forall k \in \mathcal{M}_o \cup \mathcal{B} \quad (75)$$

$$\sum_{i\in A} D_{ikt}^h \le \sum_{v\in VH}(t_D \cdot Cap_v^h \cdot Z_{vkt}^{all}) - \sum_{j\in\mathcal{L}} \sum_{v\in VH}(t_{jk} \cdot Cap_v^h \cdot Z_{jkt}^{move}), \quad \forall k \in \beta_m,\ t \in T\backslash\{n_t\} \quad (76)$$

$$\sum_{i\in A} \widetilde{D}_{ikt}^h \le \sum_{v\in VH}(t_D \cdot Cap_v^h \cdot \tilde{Z}_{vkt}^{all}) - \sum_{j\in\mathcal{L}} \sum_{v\in VH}(t_{jk} \cdot Cap_v^h \cdot \tilde{Z}_{vjkt}^{move}), \quad \forall k \in \beta_d,\ t \in T\backslash\{n_t\} \quad (77)$$

$$\sum_{i\in A} \widetilde{D}_{ikt}^g \le \sum_{v\in VA}(t_D \cdot Cap_v^g \cdot \tilde{Z}_{vkt}^{all}) - \sum_{j\in\mathcal{L}} \sum_{v\in VA}(t_{jk} \cdot Cap_v^g \cdot \tilde{Z}_{vjkt}^{move}), \quad \forall k \in \beta_d,\ t \in T\backslash\{n_t\} \quad (78)$$

$$\sum_{i\in A} \overline{D}_{ikt} \le \sum_{v\in VA}(t_D \cdot Cap_v^g \cdot (Z_{vkt}^{all} - \tilde{Z}_{vkt}^{all})) - \sum_{j\in\mathcal{L}} \sum_{v\in VA}(t_{jk} \cdot Cap_v^g \cdot (Z_{jkt}^{move} - \tilde{Z}_{vjkt}^{move})),$$
$$\forall k \in \beta_d,\ t \in T\backslash\{n_t\} \quad (79)$$

$$Z0_{vk}^{all} + Z_{vk}^{new} - Z_{vk}^{leave} + \sum_{j\in\mathcal{L}} Z_{vjk0}^{move} - \sum_{j\in\mathcal{L}} Z_{vkj0}^{move} = Z_{vk0}^{all}, \forall\ k \in \mathcal{L}, v \in VA \quad (80)$$

$$Z_{vk,t-1}^{all} + \sum_{j\in\mathcal{L}} Z_{vjkt}^{move} - \sum_{j\in\mathcal{L}} Z_{vkjt}^{move} = Z_{vkt}^{all}, \forall\ k \in \mathcal{L}, t \in T\backslash\{0, n_t\}, v \in VA \quad (81)$$

$$\sum_{k\in\mathcal{L}} Z_{vjkt}^{move} = Z_{vj,t-1}^{all}, \forall j \in \mathcal{L},\ t \in T\backslash\{0, n_t\}, v \in VA \quad (82)$$

$$\sum_{k\in\mathcal{L}} Z_{vk}^{new} = V_v^{in}, v \in VA \quad (83)$$

$$\sum_{k\in\mathcal{L}} Z_{vk}^{leave} = V_v^{out}, v \in VA \quad (84)$$

$$Z_{vk}^{leave} \le Z0_{vk}^{all}, \forall\ k \in \mathcal{L}, v \in VA \quad (85)$$

$$\sum_{v\in VA} Z_{vkt}^{all} - M \cdot U_k \le 0, \forall k \in \mathcal{P}_d, t \in T\backslash\{n_t\} \quad (86)$$

$\sum_{v \in VA} Z_{vkt}^{all} - M \cdot (U_k + Q_k^{open}) \leq 0 , \forall k \in \mathcal{P}_b, t \in T \backslash \{n_t\}$ (87)

$ZZ \geq 0$ (88)

$\bar{G}_{ikt}^1 , \tilde{G}_{ikt}^1 , \bar{G}_{ikt}^2 , \tilde{G}_{ikt}^2 \geq 0, \forall i \in A, k \in \beta_d, t \in T \backslash \{n_t\}$ (89)

$\bar{E}_{ikt} , \tilde{E}_{ikt} \geq 0, \forall i \in A, k \in \beta_m, t \in T \backslash \{n_t\}$ (90)

$D_{ikt} \geq 0, \forall i \in A, k \in \mathcal{L}, t \in T \backslash \{n_t\}$ (91)

$Z_{vkt}^{all}, Z_{vjkt}^{move}, Z_{vk}^{new}, Z_{vk}^{leave} \geq 0$ and integer,$\forall j \in \mathcal{L}, k \in \mathcal{L}, t \in T \backslash \{n_t\}$ (92)

$\tilde{Z}_{vkt}^{all}, \tilde{Z}_{vjkt}^{move} \geq 0, \forall j \in \mathcal{L}, k \in \beta_d, t \in T \backslash \{n_t\}$ (93)

$Y_{ikt} = 0$ or 1, $\forall i \in A, k \in \beta_d, t \in T \backslash \{n_t\}$ (94)

$X_{ikt} = 0$ or 1, $\forall i \in A, k \in \beta_m, t \in T \backslash \{n_t\}$ (95)

$U_k = 0$ or 1, $\forall k \in \delta_d$ (96)

$U_{jk} = 0$ or 1, $\forall j \in F_0^{in}, k \in \beta_m$ (97)

$Q_k^{open} = 0$ or 1, $\forall k \in \delta_m$ (98)

and constraints (27), (48), (2_R) and (20_R).

The objective of the model is again to minimize the weighted sum of maximum suffering and total suffering with maximum suffering as the primary concern. Suffering in this model includes both that due to waiting for evacuation and that due to shortage of relief goods.

Many constraints in this model can be understood in a similar way to that for previous models. Due to vehicle sharing, the vehicle resource requirements are calculated differently, considering both pure trips and combined trips. Constraints (61) calculate vehicle resource requirement for pure relief distribution trips. Constraints (62) and (63) calculate vehicle resource requirements for combined trips in terms of victim evacuation and relief distribution, respectively. Constraints (74) state that the number of victims sent to any potential site in a period cannot exceed the total capacity of medical facilities at the site. Constraints (75) are similar capacity constraints for existing sites. Constraints (77) and (78) ensure that, at each distribution center, the vehicles allocated to combined trips can satisfy the requirement for both victim evacuation and relief distribution in these trips. Constraints (79) ensure that the remaining vehicles in the distribution center can satisfy the requirement for the pure relief distribution trips.

4. Heuristics for Simplifying the Models

The models, especially model II, take a very long time to solve. To make the models practically useful, we have to set a time limit on their solution process. However, our test shows that, except for small problems, the solution found within the time limit is usually poor, if a feasible solution can be obtained at all. Therefore, we propose two heuristics to simplify the models to save computation time. Note that many variables in the models are defined for each of the time points in the planning horizon. Because only the result of one period is implemented, we propose to reduce the number of variables and so simplify the models by combining later time points in the models. The two heuristics do this in different ways.

In the first heuristic, the number of time points is reduced by combining more and more time points together as they are further away from the present time which is the beginning of the model planning horizon. The present time point and the next time point are kept unchanged, and so is the demand information at these two time points. The period between these first two time points remains as one time unit. It is reasonable to assume that the further away a period is from the present time, the less the information in that period would affect the decisions for the present period, and so the information may be considered in less detail. Under this assumption, therefore, the further ahead the time is, the longer the period between two adjacent new time points would be in the reduced model. The duration of each period is made one time unit longer than that of the previous period, or the same as the previous time period in cases where it is not possible to keep the period length increasing in the planning horizon. When applying the model in a rolling horizon fashion, time point reduction and information updating are performed every time the model is re-run. The coefficients of the S and W variables in the objective functions and relevant constraints in the reduced models need to be multiplied by the corresponding period lengths. Figure 4 shows examples of the periods with variable lengths in the reduced models for different runs and so with different planning horizons. This heuristic will be referred to as the *v-Length* heuristic.

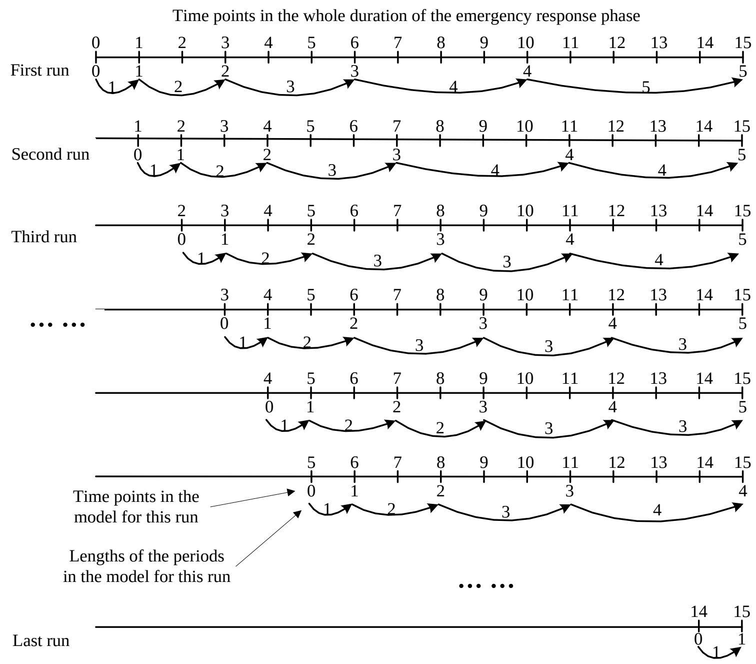

Figure 4 Time point reduction, the v-Length heuristic

The second heuristic simply keeps the first four time points (or all points if the planning horizon contains less than four points) and their related information unchanged. All the remaining time is considered as one period and therefore only one additional time point, the end of the planning horizon, will appear in the reduced models after the first four. This is also in line with the assumption that later information, after four points in this case, has less impact on the decision for the present period. The coefficients in the objective for the combined period in the reduced models need to be modified in a similar way to that in the first heuristic. Figure 5 illustrates the periods in the reduced models using this heuristic. This heuristic is henceforth referred to as the *4-Point* heuristic.

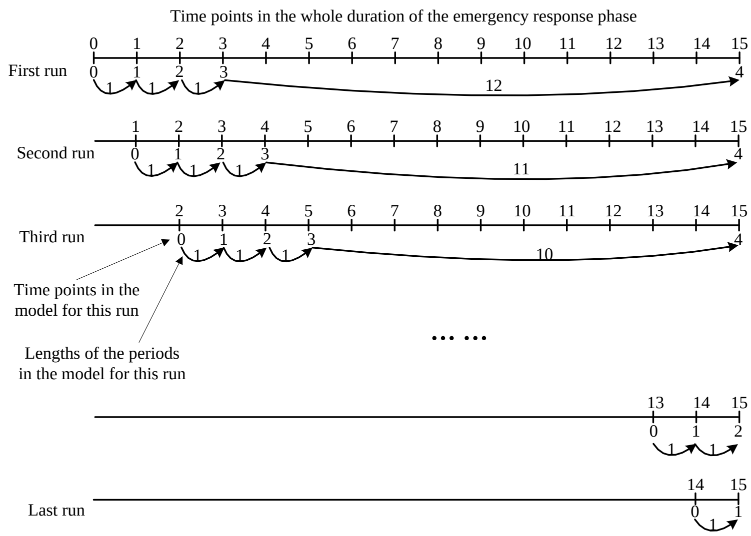

Figure 5 Time point reduction: the 4-Point heuristic

5. Computational Experiments

Computational experiments are carried out to compare the performances of the three models and hence to observe the benefit of coordination in disaster logistics operations. The experiments also test the practicality of using a standard software package to solve the models directly as well as the efficiency of the proposed heuristics.

5.1 Experiment settings

The experiments are carried out on problem instances of four different sizes defined by spatial and temporal dimensions. In the spatial dimension, large problems consist of 17 sub-regions and 47 disaster areas, the same as in the region (district) affected by the West Sumatra earthquake which has 17 sub-districts and 47 administrative areas (called nagaris); the small problems have 3 sub-regions and 9 disaster areas, representing a smaller region or a region considered in less detail. This small size is chosen in the hope of obtaining optimal or feasible solutions of the models in reasonable time. In the temporal dimension, large problems include 15 time periods (16 time points) in the emergency relief operation, again similar to that for the West Sumatra earthquake; the duration of the emergency response phase for the smaller problems has 10 time periods (11 time points), representing response to a disaster with lighter damage.

We refer to these four groups of problem instances by listing the number of time points (T), the number of sub-regions (R) and the number of disaster areas (A) in the problem, e.g., T11R3A9 indicates problems with 11 time points, 3 sub-regions and 9 disaster areas. Similarly, other problems are referred to as T11R17A47, T16R3A9 and T16R17A47, respectively. For each problem size, we generate 30 instances as described below.

In each instance, there is an existing medical center representing a provincial level hospital, and 3 potential sites for temporary medical centers. It is assumed that there are two potential sites in each sub-region for a distribution center. Other sites needed in model II are derived from the above sites. The existing hospital, for example, is allowed to have a distribution center. Travel times between different locations are generated using approximate minimum and maximum travel times based on existing places in the district.

For instances with 47 disaster areas, data about injured victims are based on those collected after the West Sumatra earthquake and data on injury-free sufferers are then calculated using these and the population in the areas. These data are then pooled into 9 disaster areas to be used for the small problems.

Information on vehicles for transporting injured victims is based on data in the response to the West Sumatra earthquake, which are obtained from the Ministry of Health Affairs office in the district. There are in total 139 such vehicles arriving at different times. Availability of vehicles at different time points varies. Information on vehicles for distributing relief, on the other hand, cannot be acquired from any sources and therefore needs to be generated. Using the total number of victim evacuation vehicles as a guideline, the average number of relief distribution vehicles newly available at each time point is about half of the number of sub-regions. Because model I requires specifying the number of vehicles for relief distribution arriving at each sub-region, the number of such vehicles for each sub-region at a certain time point is generated as 0 or 1 randomly. Because the transporting resources are limited, we assume in the experiment that the capacity of any site with medical facilities can handle the victims transported to the site.

While the objective is to minimize victim suffering, the suffering of injured victims, if not evacuated in time, is more severe than that of the non-injured victims due to lack of relief goods. Therefore, in the experiments, the weights for these two types of suffering are generated uniformly from the ranges of 10 to 20 and 1 to 10, respectively. In real applications, the weights can be set by the user based on the specific situation.

The experiments are carried out on a server with an Intel dual core Xeon 3 GHz processor and 4 GB RAM. The models are run at the beginning of each time period and the overall performances are calculated at the end of the last period, as described in Section 2.3. For each instance, the three original models are solved using the Xpress MP software. This is henceforth referred to as the *direct* solution approach. The models are also simplified using the *v-Length* and *4-Point* heuristics and then solved using Xpress MP.

For the R3A9 problems, each run of a model is limited up to 1200 seconds. For R17A47 problems, we allow a longer time due to the large problem size. On the other hand, model size decreases from one run to another. Therefore, for these large problems, a longer time limit is set for the run at the first time point. The limit is decreased for each successive run. The same idea is also used for the maximum time allocated to the cutting process in the Xpress optimizer. The maximum total run time and the maximum time for re-optimization with cutting planes are set to (5400 – 600*T) seconds and (600 – 60*T) seconds respectively for the run at time point T. Note that as model I_R consists of a sub-model for victim evacuation and a sub-model for relief distribution, the run time limit for each sub-model is set to be half of the maximum time. For model I, the time limit for the relief distribution part is split between the sub-model Ia's of the sub-regions. Apart from the maximum time limit, we also set another stopping criterion for the model runs - the run stops when a feasible solution is found within 5% of the best bound of the optimal solution.

5.2 Results and discussions

Effect magnitude can be measured to determine whether research results are practically significant (Kirk, 2007). To compare the performance of different models in terms of practical significance, we calculate Cohen's effect size *d* following Durlak (2009) with minor modifications because the objective function of our problem is to be minimized. Let M_E and SD_E be the mean and standard deviation of the objective values obtained using a method being tested, M_C and SD_C be those using another method as a reference for comparison, and *N* be the sample size, then the effect size (ES in short) *d* is calculated as follows:

$$d = \frac{M_C - M_E}{\text{Sample SD pooled}} \times \left(\frac{N-3}{N-2.25}\right) \times \sqrt{\frac{N-2}{N}}, \text{ where Sample SD pooled} = \sqrt{\frac{{SD_E}^2 + {SD_C}^2}{2}}.$$

A positive value of ES indicates that the method being tested has an improved objective mean as compared to the reference method, and a negative ES indicates otherwise. A rule of thumb is that an ES of around 0.2 is small, around 0.5 is medium, and around or above 0.8 is large in magnitude (see Durlak, 2009). In addition, we also calculate the percentage of instances that the tested method produces a positive improvement with respect to the reference method.

All four groups of problems are first solved using the direct approach, i.e., the three models are solved using the Xpress software. The comparative results are shown in Table 1. From the ES values and the percentages of improvement cases in the table it is obvious that for the two groups of small problems (T11R3A9 and T16R3A9), model II performs much better than models I and I_R, demonstrating clear benefit of coordination in disaster relief operations. Model I_R performs better than model I, indicating that even just lifting the geographical boundaries is also beneficial.

Table 1 Comparison of the models solved directly for different problem sizes

Problem size	Performance measures	I_R to I	II to I	II to I_R
T11R3A9	ES	0.27	1.64	1.53
	% of positive	83	100	100
T16R3A9	ES	0.45	1.64	1.33
	% of positive	97	100	100
T11R17A47	ES	1.54	1.51	-0.06
	% of positive	100	100	50
T16R17A47	ES	1.36	1.17	-0.76
	% of positive	100	100	10

For the large problems (T11R17A47 and T16R17A47), again both models II and I_R perform better than model I. However, model II shows similar performance to model I_R for NT11R17A47 problems, and performs slightly worse than model I_R for NT16R17A47 problems, which differs from the results for the small problems. To understand the cause of this counter-intuitive result, we look at the model size and the quality of solutions obtained at the end of the time limit. Considering the relief distribution and the victim evacuation operations together, model II is much larger than model I_R (either Ia_R, or Ib_R or total) in terms of number of variables and number of constraints. This difference in size becomes larger when the problem size increases. Observing the model solution at the end of the time limit, the objective value of the model II solution has a larger gap to the lower bound than that for model I_R, and this is more so for T16R17A47 problems. Therefore, the poor performance of model II for the large problems is due to the fact that it is larger and more difficult to solve, and a within limited time the solution obtained is still very far from the optimum. Heuristics may speed up the solution process and so better solutions may be obtained in the time limit.

More computational experiments are carried out to solve the models using the two proposed heuristics and then compare the results. Table 2 shows the results comparing the models solved using each heuristic. Table 3 compares the results of different heuristics for each model.

Table 2 Comparison of models solved using heuristics for large problems

Heuristics	Performance measures	I_R to I	II to I	II to I_R
v-Length	ES	1.40	1.46	0.49
	% of positive	100	100	70
4-Point	ES	1.42	1.50	0.61
	% of positive	100	100	77

The results in Table 2 clearly show that when being solved using either heuristic, the performance ranking of the models is in the order of model II, then model I_R and finally model I. The improvements made by models II and I_R over model I are large in magnitude, and the improvement made by model II over model I_R is medium in magnitude.

Table 3 Comparison of heuristics for each model for large problems

Model	Performance measures	v-Length to direct	4-Point to direct	4-Point to v-Length
I	ES	-0.05	-0.08	-0.02
	% of positive	37	17	37
I_R	ES	-0.26	-0.44	-0.17
	% of positive	37	23	40
II	ES	0.89	0.86	0.00
	% of positive	93	93	53

From Table 3, it can be seen that for models I and I_R, using heuristics gives slightly worse results than solving the models using the direct approach. This is because these two models are relatively small in size and the direct approach can give near optimal solutions in the time limit while the heuristics simplify the models and so sacrifice some accuracy. For model II, however, both heuristics produce much better solutions than the direct approach because of the large model size. The results also suggest that the direct approach is the best solution approach for models I and I_R. For model II, the two heuristics show similar performance, while both perform much better than the direct approach. We can choose v_Length to represent the best approach for model II.

A fairer and more useful comparison of the models is to use the results obtained by their respective best solution approaches (see Table 4). From Table 4, it is evident that when solved using their respective best solution approaches, models II and I_R perform much better than model I for all the instances tested. Model II performs slightly better than model I_R. This demonstrates that removing the restrictions imposed by the sub-region borders in relief distribution can greatly improve the effectiveness of the operation, and coordination between victim evacuation and relief distribution operations can make further improvements.

Table 4 Comparison of models solved by their best approaches for large problems

Performance measures	I_R_direct to I_direct	II_v-Length to I_direct	II_v-Length to I_R_direct
ES	1.36	1.39	0.26
% of positive	100	100	63

6. Conclusions

In this paper we have studied the problem of positioning medical and relief distribution facilities for relief operation after a sudden-onset disaster event. Three models were developed for the resource location and deployment decisions. The first model reflects the current practice of separated victim evacuation and relief distribution operations with relief distribution limited within each sub-region, the second one is a revision of the first model allowing relief distribution across the sub-region boundaries, and the third one represents coordinated operations for victim evacuation and relief distribution. The models should be run whenever there are resource availability changes considering the resources available at that time and the demand for the rest of the emergency response phase. Two heuristics were proposed to simplify the models to reduce computation time. Experiments were conducted using background information from the West Sumatra earthquake. The results showed that removing the sub-region border restrictions in relief distribution can greatly improve the effectiveness of the operation, and coordination between the victim evacuation and relief distribution operations can make further improvements. In particular, the large problem instances in the experiments are similar to the situation in the West Sumatra earthquake case where relief distributions were limited by sub-region borders. Our experiment results show that large improvement could be achieved if the restriction was removed. Future research could be done to develop more effective heuristic methods for solving the models, especially the complex model for the coordinated operations. More effective and efficient solution of the model will enhance the conclusion of this paper and will be more suitable for practical application. Road capacity may also be considered especially when deciding detailed vehicle routing.

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