Coordinated stock pre-positioning model to support emergency relief response

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Abstract. This paper aims to develop a model that coordinates the pre-positioning of critical supplies in multiple distribution centers owned by different parties or organizations. This model determines the maximum proportion of relief demand covered in multiple distribution centers and it is built to support emergency relief response in the event of an earthquake. A linear programming approach is used to solve this model. First, we assign the service area of each distribution center (Stage I). Next, by using the result of the assigned service area, we determine the minimum value of the lower bound of proportion of unsatisfied relief demand (Stage II). Afterwards, we use the output of stage II as an input to determine the maximum amount of critical relief supplies to be stocked in each distribution center (Stage III). This model is applied to the eastern part of Indonesia with 10 disaster areas and 8 existing distribution centers, of which 4 are owned by the National Agency for Disaster Management (BNPB), 2 are owned by Ministry of Health and the other 2 are owned by Indonesian Red Cross (PMI).

1. Introduction
Natural disaster such as earthquake is notorious for its uncertainty factors. Even with all the new technologies possessed in this modern age, it is still nearly impossible to predict the exact time of occurrence and the extent of the area hits by a disaster. The decision makers in disaster relief do not know when, where, what, how much, where from and how many times demand is required in the early days of the post disaster response [1]. Rather than waiting passively to launch humanitarian operations, it is better to show pro-activity by mobilizing supplies or other material and non-material resources in anticipation [2]. In this case, stock pre-positioning that involves preparing critical relief supplies in strategic locations and determining the amount of demand to be released in disaster areas is needed.

In reality, the case related to the planning of disaster operations involves many parties. These parties include the government, military, Non-Governmental Organizations (NGOs), etc. To support a quick emergency response, it is highly recommended that these parties discuss and plan the pre-positioning of critical relief supplies together in advance. Although in reality, this coordination—especially in Indonesia, is still difficult to do [3].

In the previous paper, the authors develop a stock pre-positioning model that simultaneously determines the decision of DCs to cover a single disaster area and the proportion of critical items to be stocked in each DC [4]. Their model is applied to Indonesia with 33 disaster areas and 16 DCs.
Although the tested result is satisfying, the model only considers the 16 DCs which are belong to one party: The National Agency for Disaster Management (BNPB). The other parties who also owned some DCs located in certain disaster areas and normally take part in disaster operations such as Ministry of Health (KEMKES), Indonesian Red Cross (PMI), Ministry of Social Welfare, and so on, are not considered into the model.

The later research proposes a more complex model that integrates the decisions of the maximum proportion of relief demand covered in DCs and the maximum amount of relief supplies delivered to a single disaster area within a certain period of time [5]. This research is extended to a new research that considers all potential scenarios of facility disruptions [6]. Nonetheless, these two models also do not consider the coordination of disaster operations into account. Another authors provide some crucial information about the relief logistics network structures in Indonesia [3]. They mention that the government of Indonesia has established BNPB as the policy maker and the main coordinator in the event of major disaster. They also propose two models of facility location. Their model however, do not consider the coordination of disaster operations. The next authors aim to map and analyze humanitarian logistic in Indonesia [7]. Their research focuses on the coordination of humanitarian logistic system using RASIC method. There is no mathematical model related to disaster operations is discussed in their research.

The above issues motivate us to extend the previous model developed [4] to a new stock pre-positioning model that coordinates the pre-positioning of critical relief supplies in multiple DCs owned by different parties or organizations. This new stock pre-positioning model is divided into three stages, where each stage is solved by using the Linear Programming approach. The objective of this paper is to maximize the expected relief demand covered by DCs owned by different parties.

2. Model formulation

In this model, each distribution center (DC) owned by one party is located in several different disaster areas. Each DC is assigned to provide services to one or more disaster areas that located inside the range of a given maximum response time limit (refer to Stage I). Let \( I = \{1, 2, 3, \ldots, I\} \) be the set of disaster areas, \( J = \{1, 2, 3, \ldots, J\} \) be the set of DCs owned by BNPB, \( M = \{1, 2, 3, \ldots, m\} \) be the set of DCs owned by KEMKES and \( N = \{1, 2, 3, \ldots, \bar{n}\} \) be the set of DCs owned by PMI. Let \( K = \{1, 2, 3, \ldots, \bar{k}\} \) be the set of item types. Table 1 depicts the parameters and decision variables used in this model.

Stage I: Grouping Service Area

Obj. function: Maximize \( Z = XA_{ij} + XB_{im} + XC_{in} \)  \hspace{1cm} (1)

s.t:

\[
\begin{align*}
T_{ij}X_{ij} & \leq \theta \quad \forall i \in I, j \in J \hspace{1cm} (2) \\
T_{im}X_{im} & \leq \theta \quad \forall i \in I, m \in M \hspace{1cm} (3) \\
T_{in}X_{in} & \leq \theta \quad \forall i \in I, n \in N \hspace{1cm} (4) \\
\sum_{j \in J} \sum_{m \in M} \sum_{n \in N} X_{ij}X_{im} + X_{im} + XC_{in} & \geq 2 \quad \forall i \in I \hspace{1cm} (5) \\
XA_{ij} & \in \{0,1\} \quad \forall i \in I, j \in J \hspace{1cm} (6) \\
XB_{im} & \in \{0,1\} \quad \forall i \in I, m \in M \hspace{1cm} (7) \\
XC_{in} & \in \{0,1\} \quad \forall i \in I, n \in N \hspace{1cm} (8)
\end{align*}
\]

The objective function in equation (1) maximizes the number of DCs to serve disaster areas. Constraint sets in equation (2), (3) and (4) ensure that the existing DC owned by BNPB, KEMKES and PMI, respectively, can provide service in specific disaster area if the expected time to satisfy relief demand is smaller than the maximum response time limit. Constraint set in equation (5) assures that at least two DCs will provide services in a single disaster area. Constraint sets in equation (6), (7) and (8) define the binary variables.
Parameters:
- $T_{ij}, T_{in}$: expected time to satisfy relief demand in disaster area $i$ from DC $j$ (hr), $i \in I, j \in J$; expected time to satisfy relief demand in disaster area $i$ from DC $m$ (hr), $i \in I, m \in M$; expected time to satisfy relief demand in disaster area $i$ from DC $n$ (hr), $i \in I, n \in N$, respectively.
- $\theta$: maximum response time limit to perform emergency response (hr).
- $u_k$: upper bound of the proportion of unsatisfied relief demand of item type $k$, $k \in K$.
- $m_k$: degree of importance of item type $k$; where $m_k = m$, $k \in K$.
- $P_i$: probability of occurrence of earthquake in each disaster area, $i \in I$.
- $d_{ik}$: expected demand for item type $k$ in disaster area $i$ (unit), $i \in I, k \in K$.
- $UA_j, UB_m$: capacity of DC $j$ (m$^3$), $j \in J$; capacity of DC $m$ (m$^3$), $m \in M$; capacity of DC $n$ (m$^3$), $n \in N$, respectively.
- $y_k$: unit volume of item type $k$ (m$^3$), $k \in K$.
- $BA_0, BB_0, BC_a$: pre-disaster budget of BNPB ($), pre-disaster budget of KEMKES ($), pre-disaster budget of PMI ($), respectively.
- $BA_1, BB_1, BC_c$: post-disaster budget of BNPB($), post-disaster budget of KEMKES ($), post-disaster budget of PMI ($), respectively.
- $GA_{jk}, GB_{mk}$: unit cost of acquiring item type $k$ at DC $j$ ($/unit), $j \in J, k \in K$; unit cost of acquiring item type $k$ at DC $m$ ($/unit), $m \in M, k \in K$; unit cost of acquiring item type $k$ at DC $n$ ($/unit), $n \in N, k \in K$, respectively.
- $CA_{ijk}, CB_{imk}$: unit cost of shipping item type $k$ from DC $j$ to demand point $i$ ($/unit), $i \in I, j \in J, k \in K$; unit cost of shipping item type $k$ from DC $m$ to demand point $i$ ($/unit), $i \in I, m \in M, k \in K$; unit cost of shipping item type $k$ from DC $n$ to demand point $i$ ($/unit), $i \in I, n \in N, k \in K$, respectively.
- $\alpha_k$: criticality weight for item type $k$; $\sum_k \alpha_k = 1$ and $\alpha_k \geq 0, k \in K$.
- $WA_j, WB_m$: cost of operating a single DC $j$, $j \in J$; cost of operating a single DC $m$, $m \in M$, cost of operating a single DC $n$, $n \in N$, respectively.

Decision variables:
- $XA_{ij}, XB_{im}$: set of potential DC $j$ to provide service in disaster area $i$ ($X_{ij} = 1$, if DC $j$ provides service in disaster area $i$, 0 otherwise); set of potential DC $m$ to provide service in disaster area $i$ ($X_{im} = 1$, if DC $m$ provides service in disaster area $i$, 0 otherwise); set of potential DC $n$ to provide service in disaster area $i$ ($X_{in} = 1$, if DC $n$ provides service in disaster area $i$, 0 otherwise), respectively.
- $fA_{ijk}, fB_{imk}$, $fC_{ink}$: proportion of item type $k$ relief demand satisfied by DC $j$ that provides service in disaster area $i$; proportion of item type $k$ relief demand satisfied by DC $m$ that provides service in disaster area $i$; proportion of item type $k$ relief demand satisfied by DC $n$ that provides service in disaster area $i$, respectively.
- $N_{ik}$: proportion of unsatisfied relief demand of item type $k$ in disaster area $i$ for each scenario $s$.
- $Z_k$: the lower bound of the proportion of unsatisfied relief demand of item type $k$.
- $QA_{jk}, QB_{mk}$: units of item type $k$ stored at DC $j$; units of item type $k$ stored at DC $m$; units of item type $k$ stored at DC $n$, respectively.

Stage II: Generating lower bounds of the proportion of unsatisfied demand
This stage is developed to prevent zero results of the proportions of relief demand satisfied. In this stage, the values of $XA_{ij}, XB_{im}$ and $XC_{in}$ have been determined in Stage I.

Obj. function: Minimize $Z = Z_k$

s/t: $\sum_{k \in K} fA_{ijk} \leq M XA_{ij}$ $\forall i \in I, j \in J$ (9)
$\sum_{k \in K} fB_{imk} \leq M XB_{im}$ $\forall i \in I, m \in M$ (10)
$\sum_{k \in K} fC_{ink} \leq M XC_{in}$ $\forall i \in I, n \in N$ (11)
$\sum_{j \in J} \sum_{m \in M} \sum_{n \in N} (fA_{ijk} + fB_{imk} + fC_{ink}) = 1 - N_{ik}$ $\forall i \in I, k \in K$ (12)
$N_{ik} \leq Z_k$ $\forall i \in I, k \in K$ (13)
$fA_{ijk} d_{ik} \leq QA_{jk}$ $\forall i \in I, j \in J, k \in K$ (14)
$fB_{imk} d_{ik} \leq QB_{mk}$ $\forall i \in I, m \in M, k \in K$ (15)
The objective function in equation (9) minimizes lower bound of the proportion of unsatisfied relief demand of each item type. Constraint sets in equation (10), (11) and (12) ensure the amount of supplies is stocked in a DC owned by BNPB, KEMKES and PMI, respectively, only when the DC provides service in the designated disaster area. Constraint set in equation (13) means that the actual demand is equal to the amount of satisfied relief demand summed with the amount of unsatisfied relief demand. Constraint set in equation (14) guarantees that the proportion of unsatisfied relief demand does not exceed the desired lower bound limit. Constrain sets in equation (15), (16) and (17) assure that the amount of demand is smaller than the inventory level on DC owned by BNPB, KEMKES and PMI, respectively. Constraint sets in equation (18), (19) and (20) impose the capacity restrictions on each DC. Constraint sets in equation (21) to (26) state the maximum budgets available of pre- and post-disasters programs. Constraint sets in equation (27) to (31) describe the non-negativity constraints.

Stage III: Maximizing Expected Relief Demand Covered by Distribution Centers
In this stage, the value of the upper bound of the proportion of unsatisfied relief demand is determined, where \( u_k = Z_k + (1 - Z_k) * m_k, \) \( Z_k < u_k < 1, \) and \( 0 < m_k < 1, \ \forall k \in K. \) Value of \( Z_k \) has been generated in Stage II.

Obj. function: Maximize \( Z = \sum_i \sum_j \sum_m \sum_n \sum_k \alpha_k d_{ik} f_{A_{ij}} f_{B_{mk}} f_{C_{nk}} \) \( \forall i \in I, k \in K \) (32)

s/t:
\[
N_{ik} \leq u_k \quad \forall i \in I, k \in K
\] (33)

The objective function in equation (32) is now maximizing the total expected relief demand by each DC. Constraint set in equation (14) is now replaced by constraint set in equation (33) that guarantees the proportion of unsatisfied relief demand in each disaster area is smaller than the desired upper bound limit. The rest of the constraints are remaining the same (refer to Stage II).

3. Data construction
For the sake of simplicity, in this paper we apply our model to the eastern part of Indonesia with 10 disaster areas. According to the data provided by [3], there are 8 existing distribution centers located in eastern Indonesia, of which 4 are owned by BNPB, 2 are owned by KEMKES and the other 2 are owned by PMI. The disaster areas are: (1) South Sulawesi—with one existing DC, (2) West Sulawesi,
Table 2. Data estimation

| Exp. resp. time (hr) | Distance from DC to affected area (km) / vehicle speed (km/hr) + (expected loading time (hr)). |
|---------------------|--------------------------------------------------------------------------------------------------|
| Max. resp. time (hr) | Expected to be 8 hours (the same for each disaster area).                                       |
| Probability of earthquake | Calculated based on the frequency of earthquakes hit each disaster area during 2005-2013. The earthquakes magnitude varies between 1.0 to 9.0 Mw. |
| Demand | Assumed to be 50% of the total population of each province in year 2010. |
| Criticality weight | Weight of item type A to D = 0.286, 0.286, 0.286 and 0.143, respectively. |
| Volume (m³) | Unit volume of item type A to D = 0.018, 0.054, 0.054, and 0.200, respectively. |
| DC capacity (m³) | Dimension of each DC is assumed to be 100 x 100 x 12 = 120,000 m³. Normally, only 70% space is used for the storage. The capacity of DCs owned by BNPB is 84,000 m³ (the same for each DC). While the capacities of DCs owned by KEMKES and PMI are assumed to be 25,200 m³ and 42,000 m³, respectively (the same for each DC). |
| Cost of operating a DC ($) | For each DC owned by BNPB, KEMKES and PMI, the costs are assumed to be $6,100/5 years, $1,830/5 years and $3,050/5 years (the same for each DC). (1 USD = 13,300 IDR). |
| Unit cost of acq. ($) | Purchase cost of item type A to D = $236.842, $2,406, $488.722 and $751.445, respectively. |
| Unit cost of ship. ($) | (Expected response time (hr)) x (fuel needed (liter/hr)) x 2 (round trip). |
| Maximum budgets available ($) | Pre-disaster budgets of BNPB, KEMKES, PMI assumed to be $857,317,919.075 (100%); $257,195,375.722 (30%) and 428,658,959.537 (50%); respectively. |
| | Post-disaster budgets of BNPB, KEMKES, PMI assumed to be $116,589,595.375 (100%); $34,976,878,612 (30%) and $58,294,797.687 (50%); respectively. |

4. Computational results and analysis

LINGO 8.0 is used for finding the optimal solutions. All experiments solving each problem are tested on a personal computer with an Intel® Core™ 2 Duo CPU 2.93GHz and 2.00 GB of RAM. The computation time of all the test problems is less than 3 minutes. The result of stage I, which is grouping service area for each distribution center (DC), stated that for all DCs located in Makassar (owned by BNPB, KEMKES and PMI) can provide service to all disaster areas except West Papua and Papua, while all DCs located in Manado (owned by BNPB, KEMKES and PMI) can provide service to all disaster areas except Papua, and DC located in Ambon (owned by BNPB) can provide service to all disaster areas. Meanwhile, DC located in Papua (owned by BNPB) can only provide services to Gorontalo, Maluku, West Papua and Papua. From the results also can be stated that Papua receives the least services compared to the other disaster areas due to its remote location.

The results of stage II, which is the lower bound of proportion of unsatisfied relief demand (for item type A to D) are all 0.000. These results are used as inputs in stage III. Furthermore, in stage III, we set the value of degree of importance of each item type (denoted by $m_k$) to be 0.85. Thus, the result of total expected relief demand covered by distribution centers is 109,577,900 (objective function). Table 3 shows the result of the proportion of satisfied relief demand in disaster area 9 (West Papua) for all item types. In this case, DCs 3 and 4 (owned by BNPB) are covering half of the items type B (instant food), type C (drinking water) and type D (tent) to be sent to West Papua, while the other half is covered by DC 2 owned by PMI. Meanwhile, DC 2 owned by KEMKES is covering 100% of item type A (medicine). Table 4 shows the result of the total proportion of satisfied relief demand in each disaster area. Given the assumption of budgets available and 50% of the total population in each disaster area that will be affected by the earthquake and needed to be treated immediately, disaster area 1 to 9 (South Sulawesi to West Papua) can be covered 100% (1,000), while

(3) South East Sulawesi, (4) Central Sulawesi, (5) Gorontalo, (6) North Sulawesi—with one existing DC, (7) North Maluku, (8) Maluku— with one existing DC, (9) West Papua, (10) Papua—with one existing DC. The 4 DCs owned by BNPB are located in: (1) Makassar, (2) Manado, (3) Ambon, (4) Jayapura. The 2 DCs owned by KEMKES and 2 DCs owned by PMI are located in the same cities: (1) Makassar, (2) Manado. Table 2 describes the data estimation. The critical item types are: (A) Medicine (box), (B) Instant food (box), (C) Drinking water (box) and (D) Tent (unit). In this case, DCs owned by KEMKES can only be used to stock medical supplies (item type 1). Helicopters are used to transport each item to disaster area.
disaster area 10 (Papua) can be covered only as big as 99.2% (0.992) for item type A, 15% (0.150) for item type B and type C, and 23.7% (0.237) for item type D.

| DC  | Item type | A     | B     | C     | D     |
|-----|-----------|-------|-------|-------|-------|
|     |           | 0.0   | 0.0   | 0.0   | 0.0   |
| BNPB| 1         | 0.0   | 0.0   | 0.0   | 0.0   |
|     | 2         | 0.0   | 0.0   | 0.0   | 0.0   |
|     | 3         | 0.0   | 0.5   | 0.0   | 0.0   |
|     | 4         | 0.0   | 0.0   | 0.5   | 0.5   |
| KEMKES| 1       | 0.0   | 0.0   | 0.0   | 0.0   |
|     | 2         | 1.0   | 0.0   | 0.0   | 0.0   |
| PMI            | 1         | 0.0   | 0.0   | 0.0   | 0.0   |
|     | 2         | 0.0   | 0.5   | 0.5   | 0.5   |

| Disaster area | Item type | A     | B     | C     | D     |
|---------------|-----------|-------|-------|-------|-------|
| 9             | 1         | 0.992 | 0.150 | 0.150 | 0.237 |

Compared to the previous papers as discussed in the Introduction part, especially one written by [4], this paper considered multiple DCs owned by different parties, in this case BNPB, KEMKES, and PMI. This paper gives a solution to determine the optimum number of critical items to be stocked in each DC owned by different parties based on the available budgets and capacity restrictions. This coordinated stock pre-positioning model can minimize the oversupply and/or undersupply of critical items at the affected areas which will lead to the improvement of the emergency relief response.

5. Conclusion and future work

This paper proposes a new model that coordinates the pre-positioning of critical relief supplies in multiple distribution centers (DCs) owned by different parties. This model applied to eastern Indonesia with 10 disaster areas and 8 existing distribution centers, of which 4 are owned by the National Agency for Disaster Management (BNPB), 2 are owned by Ministry of Health (KEMKES) and the other 2 are owned by Indonesian Red Cross (PMI). The result of Stage I (grouping service area) shows that West Papua and Papua receive the least services from DCs compared to other disaster areas due to its remote location. Based on the results of the final stage, the proportions of satisfied relief demand in most disaster areas, except in Papua, can be fully satisfied. This coordinated stock pre-positioning model can minimize the oversupply and/or undersupply of critical items at the affected areas. As for the future work, we will consider the distribution or transportation planning problem into the model.

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