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A Stock Pre-positioning Model to Maximize the Total Expected Relief Demand of Disaster Areas

Woon-Seek Lee
Department of Systems Management and Engineering, Pukyong National University, Busan, Korea

Byung Soo Kim*
Department of Industrial and Management Engineering, Incheon National University, Incheon, Korea

Prudensy Febreine Opit
Department of Industrial Engineering, De La Salle Catholic University, Manado, Indonesia

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ABSTRACT

Stock pre-positioning is one of the most important decisions for preparing the stage of emergency logistics planning. In this paper, a mixed integer model for stock pre-positioning is derived to support an emergency disaster relief response against the event of earthquake. A maximum response time limit, budget availability, multiple item types, and capacity restrictions are considered. In the model, the decision of the distribution centers to cover a disaster area and the amount of supplies to be stocked in each distribution center are simultaneously determined to maximize the total expected relief demand of the disaster areas covered by the existing distribution centers. The proposed model is applied to a real case with 33 disaster areas and 16 distribution centers in Indonesia. Several sensitivity analyses are conducted to estimate the fluctuation on the emergency stock pre-positioning planning by changing the maximum response time and budgets.

Keywords: Disaster Relief, Stock Pre-positioning, Emergency Logistics Response

* Corresponding Author, E-mail: bskim@incheon.ac.kr

1. INTRODUCTION

Natural disasters, such as earthquakes, tsunamis, floods, landslides, volcanic eruptions, or typhoons, come along with various uncertainty factors, which made it difficult to predict disaster areas. This leads to increase the importance of emergency logistics planning for disaster areas. There are many issues in the pre-positioning stage of relief-item stocks including budget limitation, limited number of distribution center, and limited capacity for each distribution center with unknown demand of the relief-items. Once a disaster happens in certain areas, the relief-items for the areas are requested and the demands must be efficiently transported to the corresponding disaster areas. Because the demands are lumpy and arise suddenly in areas completely unknown until the disaster occurs, the stock pre-positioning planning for the demands is critical for emergency disaster relief (Beamon, 2004).

Recently, the field of emergency disaster relief logistics planning has received much more attention and various interesting models have been proposed. Beamon and Kotleba (2006) developed a stochastic inventory control model that determines optimal order quantities and reorder points for a long-term emergency disaster relief response. Meanwhile, Ozbay and Ozguven (2007) presented an efficient and quick-response humanitarian inventory management model to determine the safety stock that will prevent disruptions at a minimal cost using a version of Hungarian inventory control model and proposed a solution by using the *p*-efficient point (pLEPs) algorithm.

Tovia (2007) proposed an emergency response model that can be used by offices of emergency preparedness to evaluate response capabilities, to assess the logistics challenges in the event of natural disaster, specifically hurricane, and to perform what-if analysis on the threat of a weather disturbance system. Chang *et al.* (2007) applied the data processing and network analysis functions of the geographic information system to estimate the possible locations of rescue demand points and the required amount of rescue equipment for flood emergency logistics. Yi and Ozdamar (2007) developed an integrating location-routing model for coordinating logistics support and evacuation operations in response to emergencies and natural disasters.

Ratick *et al.* (2008) focused specifically on locating backup facilities to support supply chain disaster resilience using the set cover location modeling as a decision aid. Two years later, Gatignon *et al.* (2010) evaluated the decentralized supply chain's performance in responding to humanitarian crises through an analysis of the International Federation of Red Cross and Red Crescent Societies (IFRC)'s operations during the Yogyakarta earthquake in 2006. Balcik and Beamon (2008) developed a humanitarian relief model that determines the number and locations of distribution centers in a relief network. Their model also determines the amount of relief supplies to be stocked at each distribution center to meet the needs of people affected by the disasters. They considered multiple item types and captured budgetary constraints and capacity restrictions. They also provided the simulation of pre- and post-disaster relief funding on relief system's performance. Ortuno *et al.* (2011) proposed a two phase solving method based on lexicographical goal programming to deliver the planned quantity of goods and to do so in the best possible way.

In this paper, we deal with stock pre-positioning planning problem to support an emergency disaster relief response against the event of earthquake by carefully considering the response time needed for each existing distribution center to serve one or more disaster areas.

This paper are mentioned as follows: we first derived a mixed integer programming model that simultaneously determines the decision of the distribution centers to cover a disaster area and the amount of supplies to be stocked in each distribution center to maximize the total expected relief demand of disaster areas covered by the existing distribution centers. Then, we simulated the model to a stock pre-positioning planning based on the real historical data in Indonesia, one of the earthquake-prone countries in Asia.

2. MODEL FORMULATION

In this section, we propose a mixed integer programming model for stock pre-positioning planning. For the model, each distribution center is located in a single disaster area, and each distribution center can provide service in more than one disaster areas. We assume that the earthquake will not occur at the same time in multiple disaster areas.

- Data sets

I	set of candidate disaster areas
J	set of distribution centers
K	set of item types
J^i	set of distribution centers that provide service to disaster area i

- Parameters

T_{ij}	expected time to satisfy relief demand in disaster area i from distribution center j (hour)
δ_i	maximum response time limit to perform emergency response in disaster area i (hour)
P_i	probability of occurrence of earthquake in disaster area i
d_{ik}	expected demand for item type k in disaster area i (unit)
U_j	capacity of distribution center j (m^3)
γ_k	unit volume of item type k (m^3)
B_0	pre-disaster budget ($)
B_1	post-disaster budget ($)
g_{jk}	unit cost of acquiring item type k at distribution center j ($/unit)
c_{ijk}	unit cost of acquiring item type k from distribution center j to disaster area i
w_k	criticality weight for item type k; $\sum_{k\in K} w_k = 0$ and $w_k \geq 0$
M	a very large positive number

- Decision variables

f_{ijk}	proportion of item type k relief demand satisfied by distribution center j that provide services in disaster area i
Q_{ik}	unit item type k stored in distribution center j
a_{ij}	1, if expected time to satisfy relief demand in disaster area i from distribution center j is no longer than the maximum response time limit; 0, otherwise
X_{ij}	1, if distribution center j provides service in disaster area i; 0, otherwise

- The mixed integer programming can be formulated as follows:

$$\textit{Minimize} \quad \sum_{i\in I}\sum_{k\in K}\sum_{j\in J^i} p_i d_{ik} w_k f_{ijk} \tag{1}$$

$$\textit{Subject to} \quad \sum_{k\in K} f_{ijk} \leq MX_{ij}, \qquad \text{for} \;\; \forall\, i\in I,\, j\in J, \tag{2}$$

$$\sum_{j\in J} f_{ijk} \leq 1, \qquad \text{for} \;\; \forall\, i\in I,\, k\in K, \tag{3}$$

$$f_{ijk} d_{ik} \leq Q_{ik}, \qquad \text{for} \;\; \forall\, i\in I,\, j\in J,\, k\in K, \tag{4}$$

$$\sum_{k\in K} \gamma_k Q_{jk} \leq U_j, \qquad \text{for} \;\; \forall\, j\in J, \tag{5}$$

$$\sum_{j\in J}\sum_{k\in K} Q_{ik} g_{jk} \le B_0 \qquad (6)$$

$$\sum_{k\in K}\sum_{j\in J} d_{ik} c_{ijk} f_{ijk} \le B_1, \quad \text{for} \ \forall\, i \in I, \qquad (7)$$

$$f_{ijk} \ge 0, \quad \text{for} \ \forall\, i \in I,\ j \in J,\ k \in K, \qquad (8)$$

$$a_{ij} T_{ij} \le \delta_i, \quad \text{for} \ \forall\, i \in I,\ j \in J, \qquad (9)$$

$$a_{ij} \ge X_{ij}, \quad \text{for} \ \forall\, i \in I,\ j \in J, \qquad (10)$$

$$\sum_{j\in J} X_{ij} \le 1 \quad \text{for} \ \forall\, i \in I, \qquad (11)$$

$$a_{ij} \in (0, 1) \quad \text{for} \ \forall\, i \in I,\ j \in J, \qquad (12)$$

$$X_{ij} \in (0, 1) \quad \text{for} \ \forall\, i \in I,\ j \in J, \qquad (13)$$

The objective function (1) maximizes the total expected relief demand covered by the existing distribution centers. Constraint (2) ensures the amount of supplies sent to satisfy relief demand only exists when the distribution center provides service in designated disaster areas. Constraint (3) ensures the amount of supplies sent to satisfy relief demand in specific disaster area does not exceed the actual demand. Constrain (4) ensures the inventory level at a single distribution center is no smaller than the maximum amount of demand. Constraint (5) guarantees that the amount of inventory kept at any distribution center does not exceed its capacity. Constraint (6) requires that the preparedness expenditures related to provision of logistics for basic needs in emergency does not exceed the pre-disaster budget. Constraint (7) requires that the transportation costs to mobilize resources are less than the expected post-disaster budget. Constraint (8) non-negativity constraint on the proportion of demand satisfied. Constraint (9) guarantees that the existing distribution center can only provide service in specific disaster area if the expected time to satisfy relief demand is no bigger than the maximum response time limit. Constraint (10) guarantees that a distribution center will not provide service in specific disaster area if the expected time to satisfy relief demand is bigger than the maximum response time limit. Constraint (11) assures that there is at least one distribution center will provide service in any disaster area. Constraints (12) and (13) define the binary variable of potential response time and service area for each distribution center.

For applying a real case in Indonesia, we make an adjustment to the model formulation. The general form of Constraint (11) is changed to:

$$\sum_{j\in J} X_{ij} \ge 2, \quad \text{for} \ \forall\, i \in I_1 \qquad (13a)$$

$$\sum_{j\in J} X_{ij} \ge 1, \quad \text{for} \ \forall\, i \in I_0 \qquad (13b)$$

Constraint (13a) assures that at least two distribution centers must provide services to a set of disaster area that already has one existing distribution center (I_1) and Constraint (13b) assures that at least one distribution center must provide service to a set of disaster area with zero existing distribution center (I_0).

3. DATA GENERATION

Indonesia is located in the south-eastern region in Asia with a total population of more than 230 million in 2011. Indonesia is considered as an earthquake-prone country because three major plates frequently cause massive earthquake when they collide each other. According to the official website of Meteorology, Climatology and Geophysics Agency of Indonesia (http://www.bmkg.go.id), in 2010, Indonesia was hit by 289 events of earthquake range from 1.0 to 9.5 Mw.

Table 1 shows the number of disaster areas, distribution centers, and item types for the model testing. Number of disaster areas is 33 based on 33 provinces existed in Indonesia in 2011. Number of distribution centers is 16. They are located in 16 different disaster areas. In this case, a distribution center serves one or more disaster areas and one disaster area possibly served by one or more distribution centers. Commonly, disaster relief consists of many items. The items needed are very diverse and difficult to be accurately satisfied. In this paper, the items are limited up to nine critical item types.

Table 1. Data set

No. of disaster area (33)	1. Aceh*; 2. North Sumatra*; 3. Riau*; 4. West Sumatra; 5. Jambi; 6. Riau Island; 7. Bangka-Belitung; 8. Bengkulu; 9. South Sumatra*; 10. Lampung*; 11. Banten*; 12. Jakarta; 13. West Java; 14. Central Java; 15. Yogyakarta*; 16. East Java*; 17. Bali; 18. West Nusa Tenggara*; 19. East Nusa Tenggara*; 20. West Kalimantan; 21. Central Kalimantan*; 22. South Kalimantan; 23. East Kalimantan*; 24. West Sulawesi; 25. South Sulawesi*; 26. South East Sulawesi; 27. Central Sulawesi*; 28. Gorontalo*; 29. North Sulawesi; 30. North Maluku; 31. Maluku*; 32. West Papua; 33. Papua
No. of distribution center (16)	1. Banda Aceh; 2. Medan; 3. Tanjung Pinang; 4. Palembang; 5. Bandar Lampung; 6. Serang; 7. Yogyakarta; 8. Surabaya; 9. Mataram; 10. Makassar; 11. Kupang; 12. Palangkaraya; 13. Samarinda; 14. Palu; 15. Gorontalo; 16. Ambon
No. of item type (9)	A. Medicine (*box*); B. Instant food (*box*); C. Rice (*per* 50 *kg*); D. Drinking water (*box*) E. Blanket (*unit*); F. Clothes (*packet*); G. Tent (*unit*); H. Mat (*unit*); I. Lantern lamp (*unit*)

[*] means disaster area with one existing distribution center.

Table 2 depicts the data estimation. Related to the calculation of expected response time, helicopters are used to transport each item to the affected area. The expected loading time is set to be 2 hours (the same for each item). The maximum response time limit is set to be 8 hours, while in the reality this number is flexible depends on the government policy. The probability of earthquake for each disaster area is estimated by the team of Indonesia's earthquakes map revision using the principal of 6 earthquake zones of Indonesia (National Agency for Disaster Management of Indonesia, 2009). Indonesia population in 2010 is used for the demand estimation while criticality weights are obtained by classifying all items into two groups: primary and secondary items. The capacity of each distribution center is obtained by assuming the dimension of each distribution center is 100×100×12 = 120,000 m³. Normally, only 70% space is used for the storage. Hence, the capacity of each distribution center is 84,000 m³. Unit cost of acquiring relief item is estimated from the purchase price of each item. To calculate the unit cost of shipping, it is necessary to assume the maximum load of helicopter. The maximum load of medium size of helicopter can be assumed to be 6.23 m³ for one way trip. It is also important to be noticed that pre- and post-disaster budgets were predetermined by the government. In this paper, maximum pre- and post-disaster budgets were adapted from the budget allocation of Indonesian government in 2010–2014 (National Agency for Disaster Management of Indonesia, 2009).

4. COMPUTATION RESULTS

LINGO 8.0 was used for finding the optimal solutions with the mathematical model presented in Section 2. All experiments solving each problem are tested on a personal computer with an Intel Core2 Duo CPU 2.93 GHz and 2.00 GB of RAM. The computation time of all the test problems was less than 1 minute.

Several sensitivity analyses are performed by changing two sensitive parameters, the maximum response time and budgets. For first sensitivity analysis, we want to know how many distribution centers are covered for each disaster area as the maximum response time is changed as 7.3, 8, 10, and 12 hours. Table 3 shows the results of the number of distribution centers covered for each disaster area in each maximum response time. A

Table 2. Data estimation

Expected response time	Distance from distribution center to the affected area (km) / Vehicle speed (km/hr) + Expected loading time (hr)
Maximum response time	Expected to be 8 hours since the earthquake (the same for each disaster area).
Probability of earthquake	Calculated based on the frequency of earthquake hit each disaster area during the last 6 years (2005–2010). The earthquake magnitude varies between 1.0 to 9.0 Mw.
Amount of demand	Estimated from the total population of each province in 2010.
Criticality weight	Weight of each item type/Total weight (Weight of item types A to I are 0.13, 0.13, 0.13, 0.13, 0.07, 0.13, 0.13, 0.07, and 0.07 kg, respectively)
Volume	Unit volume of items A to I type are 0.01887, 0.05400, 0.02000, 0.05400, 0.0090, 0.11190, 0.20000, 0.05625, and 0.00562 m³, respectively.
Distribution center capacity	84,000 m³
Unit cost of acquiring relief items	Unit cost of item types A to I are \$364.162, \$5.78, \$0.925, \$3.699, \$6.936, \$11.561, \$751.445, \$8.671, and \$8.092, respectively.
Unit cost of shipping from distribution center to the affected area	Expected response time (hr) × Kerosene needed (L/hr) × 2 (round trip)
Maximum pre-disaster budget available	\$857,317,919.075
Maximum post-disaster budget available	\$116,589,595.375

\$1.00 (USD)/rp. 8,650.

Table 3. Number of distribution centers to cover a single disaster area

Max response time (hr)	Disaster area																															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33
7.3	3	6	7	7	9	9	10	9	9	9	10	9	10	11	11	12	12	11	9	12	13	13	10	10	10	9	10	8	7	6	6	2	1
8	4	6	9	9	10	10	13	9	11	10	11	12	12	12	12	13	12	13	10	13	13	13	14	12	11	10	10	9	8	7	7	2	1
10	5	9	12	11	11	14	14	13	14	14	15	15	15	15	15	15	14	14	11	15	15	15	14	14	14	13	14	14	10	9	10	6	2
12	10	13	14	14	15	15	16	15	15	16	16	16	16	16	16	16	15	15	14	16	16	16	16	15	15	14	15	14	14	14	12	9	5

Table 4a. Total inventory under varying budgets and response time for item types A, B, C, and D

Max response time (hr)	Pre-disaster budget ($)	Post-disaster budget ($)	Total expected relief demand (unit)	Total inventory (m^3)			
				A (medicine)	B (instant food)	C (rice)	D (drinking water)
7.3	857,317,919	116,589,595	17,165,980	33,214	93,382	598,727	155,636
	1,071,647,398	116,589,595	17,433,320	43,935	93,382	598,727	155,636
	857,317,919	145,736,994	17,165,980	33,214	93,382	598,727	155,636
	857,317,919	1,165,895,953	17,165,980	33,214	93,382	598,727	155,636
	8,573,179,190	1,165,895,953	19,529,000	362,528	48,602	410,106	91,510
8	857,317,919	116,589,595	17,979,240	33,235	82,170	538,295	142,561
	1,071,647,398	116,589,595	18,298,410	44,407	82,170	543,905	136,951
	857,317,919	145,736,994	17,979,240	33,235	82,170	538,295	142,561
	857,317,919	1,165,895,953	17,979,240	33,235	82,170	538,295	142,561
	8,573,179,190	1,165,895,953	20,441,220	268,004	68,908	405,945	114,847
10	857,317,919	116,589,595	20,015,700	33,293	82,170	573,531	152,078
	1,071,647,398	116,589,595	20,390,350	44,469	82,170	583,084	142,525
	857,317,919	145,736,994	20,021,410	33,293	82,170	573,531	152,078
	857,317,919	1,165,895,953	20,021,410	33,293	82,170	573,531	152,078
	8,573,179,190	1,165,895,953	22,814,930	295,291	80,464	349,515	135,815
12	857,317,919	116,589,595	21,136,780	34,443	82,170	463,857	136,951
	1,071,647,398	116,589,595	21,554,790	44,950	82,170	455,021	136,951
	857,317,919	145,736,994	21,304,790	34,311	82,170	420,623	136,951
	857,317,919	1,165,895,953	21,309,920	34,311	82,170	420,623	136,951
	8,573,179,190	1,165,895,953	24,303,170	244,974	82,170	420,623	136,951

Table 4b. Total inventory under varying budgets and response time for item types E, F, G, H, and I

Max response time (hr)	Pre-disaster budget ($)	Post-disaster budget ($)	Total expected relief demand (unit)	Total inventory (m^3)				
				E (blanket)	F (clothes)	G (tent)	H (mat)	I (lantern lamp)
7.3	857,317,919	116,589,595	17,165,980	145,122	276,706	0.00	24,703	16,507
	1,071,647,398	116,589,595	17,433,320	157,909	253,197	0.00	24,703	16,507
	857,317,919	145,736,994	17,165,980	145,122	276,706	0.00	24,703	16,507
	857,317,919	1,165,895,953	17,165,980	145,122	276,706	0.00	24,703	16,507
	8,573,179,190	1,165,895,953	19,529,000	189,152	200,816	0.00	21,286	19,996
8	857,317,919	116,589,595	17,979,240	137,843	356,910	0.00	36,475	16,507
	1,071,647,398	116,589,595	18,298,410	137,843	345,737	0.00	36,475	16,507
	857,317,919	145,736,994	17,979,240	137,843	356,910	0.00	36,475	16,507
	857,317,919	1,165,895,953	17,979,240	137,843	356,910	0.00	36,475	16,507
	8,573,179,190	1,165,895,953	20,441,220	189,152	249,826	0.00	24,703	22,611
10	857,317,919	116,589,595	20,015,700	142,340	308,930	0.00	36,475	15,179
	1,071,647,398	116,589,595	20,390,350	142,340	297,753	0.00	36,475	15,179
	857,317,919	145,736,994	20,021,410	142,340	308,930	0.00	36,475	15,179
	857,317,919	1,165,895,953	20,021,410	142,340	308,930	0.00	36,475	15,179
	8,573,179,190	1,165,895,953	22,814,930	187,364	254,079	0.00	21,286	20,181
12	857,317,919	116,589,595	21,136,780	116,839	461,462	0.00	42,189	6,085
	1,071,647,398	116,589,595	21,554,790	116,839	450,697	0.00	42,189	15,179
	857,317,919	145,736,994	21,304,790	116,839	503,573	0.00	43,443	6,085
	857,317,919	1,165,895,953	21,309,920	116,839	503,573	0.00	43,443	6,085
	8,573,179,190	1,165,895,953	24,303,170	121,678	294,857	0.00	24,703	17,567

single distribution center could only provide service into one or more disaster areas if the expected time to satisfy relief demand in affected disaster area is less than the maximum response time limit in order to perform an emergency response. Total number of distribution centers that will provide service in a disaster area is varying by indexing from 1 to 16. As the response time become larger, the larger number of distribution centers are covered for each distribution center. Disaster area no. 33 (Papua) located in eastern part of Indonesia, where the area is the most isolated candidate disaster area, is covered by the minimum number of distribution center, varying by indexing from 1 to 5. Disaster area no. 16 and 20 (East Java and West Kalimantan) located in the middle of Indonesia provided the highest relief service that varying from 12 to the maximum of 16 distribution centers.

The second sensitivity analysis performed the total volumes of inventory stocked in distribution centers under varying response time and budgets. The pre- and post-disaster budgets and total expected relief demands shown in Table 4a and 4b are determined by referring from National Agency Disaster Plan of Indonesian government (2009). In the planning report, the original budgets set by \$857,317,919 and \$116,589,595. If the maximum response time is set to be 7.3 hours, then the total expected relief demand for all items stored in the distribution centers is determined to 17,165,980 units. Item type C (rice) spent the most space in distribution centers with the total volume of 598,727 m^3, while item type G (tent) is the opposite with zero unit purchased. This result was due to the high price and large volume for one unit of tent compared to another item. In the second case (second row), we increased the pre-disaster budget by 25% of its original budget and maintain the same number of post-disaster budget. Next, the third case, we increased the post-disaster budget by 25% and maintain the same number of pre-disaster budget. In the fourth case, we increased the post-disaster budget tenfold greater than the original budget in order to make it bigger than the pre-disaster budget. Finally, in the last case, we increased the two budgets tenfold greater than the original budget simultaneously. As we increased the pre-disaster budget, the result shown in Table 4 was fluctuated. The result of total expected relief demand was varied with the maximum of 19,529,000 units in the last case and the minimum of 17,165,980 units in the first, third, and fourth cases. A sensitivity analysis was then performed for the rest maximum response time. The result showed the fluctuation of total expected relief demand and total volume of inventory in distribution centers. As the pre-disaster budget increases while the post-disaster budget remains the same, the total expected demand increases. As the post-disaster budget increases while the pre-disaster budget remains the same, the result does not change. This indicates that the post-disaster budget does not affect the total inventory of all items. If we increased the two budgets simultaneously in a very large number, the result becomes steady because the capacity of each distribution center has reached its limit.

5. CONCLUSIONS

In this paper, we proposed a modified model of emergency deployment that focused on preventing the result of zero proportion of a single item type stored in distribution centers. The proposed model is applied to a real case in which 33 disaster areas and 16 distribution centers in Indonesia were involved. The result showed an improvement compared to the result generated by the previous model. By adding a new variable of proportion of unsatisfied relief demand, the amount of each item type stocked in the distribution centers is no longer zero. This result satisfies the Indonesian government policy that requires the availability of each item type in distribution centers.

This paper leads to several directions for future research. We found that it is very interesting to coordinate the transportation of commodities from the distribution centers to the disaster area and enable the selection of the best locations of distribution centers to dispatch the demand in disaster area. Our future research will become more complex because we are planning to integrate the three problems of logistics coordination—facility location, stock pre-positioning, and transportation. This future research is expected to result in higher accuracy and more output compared to solving the problems individually.

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