Humanitarian Relief Logistics with Time Restriction: Thai Flooding Case Study

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ABSTRACT
Shortages and delays in a humanitarian logistics system can contribute to the pain and suffering of survivors or other affected people. Humanitarian logistics budgets should be sufficient to prevent such shortages or delays. Unlike commercial supply chain systems, the budgets for relief supply chain systems should be able to satisfy demand. This study describes a comprehensive model in an effort to satisfy the total relief demand by minimizing logistics operations costs. We herein propose a strategic model which determines the locations of distribution centers and the total inventory to be stocked for each distribution center where a flood or other catastrophe may occur. The proposed model is formulated and solved as a mixed-integer programming problem that integrates facility location and inventory decisions by considering capacity constraints and time restrictions in order to minimize the total cost of relief operations. The proposed model is then applied to a real flood case involving 47 disaster areas and 13 distribution centers in Thailand. Finally, we discuss the sensitivity analysis of the model and the managerial implications of this research.

Keywords: Humanitarian Logistics, Relief Supply Chain, Disaster Management, Optimization

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1. INTRODUCTION

By 2015, on average, over 375 million people per year are likely to be affected by climate-related disasters. This exceeds the average yearly figures for the past decade by more than 50% (Ganeshan and Diamond, 2009). Such global disasters appear to test our emergency response systems. When words like super hurricane, tsunami, or earthquake appear in the headlines, we expect aid and resources to be rapidly distributed so as to relieve human suffering. The government response to a disaster is often criticized for mismanagement and lack of preparation. In order to ensure the effectiveness of relief effort systems, humanitarian relief organizations must understand the importance of relief chain management in the disaster relief operations (Van Wassenhove, 2006).

Recent studies have demonstrated the increasing contribution of relief supply chain management due to the increasing number of natural and man-made disasters and have clarified the central role of logistics in responding to these disasters (Kovacs and Spens, 2012). Among the number of contributions in this field, the optimization models encompass most objective challenges. Studies of this topic can be grouped into three categories according to model type based on logistics characteristics: the facility location model, the distribution model, and the inventory model (Manopiniwes and Irohara, 2014).

Facility location and inventory models are popular for use in solving problems that focus on the pre-disaster stage, whereas the distribution model is primarily applied to problems that focus on the post-disaster phase. This characteristic is affected by the necessary activities related in each period of disaster lifecycle system. First, the research indicates that the most important factor in disaster preparedness is to determine the locations of facilities and infrastructure, including, but not limited to, central warehouses, local warehouses, permanent relief facilities (such as major hospitals and positioned relief equipment...
and vehicles), and temporary relief facilities (such as mobile hospitals). Moreover, humanitarian logistics systems are usually required to keep some of their required relief items and equipment in stock, in order to increase their levels of preparedness against sudden disasters. However, similar to commercial supply chains, high levels of inventory holding costs could be a burden on humanitarian organizations because of their limited funds and operating resources. Therefore, designing effective supply chain and logistics systems for humanitarian organizations is of great importance (Nikbakhsh and Zanjirani Farahani, 2011). Kongsomsaksakul et al. (2005) investigated optimal shelter locations for flood evacuation planning. McCall (2006) developed and suggested prepositioning of humanitarian assistance pack-up kits that contain commonly used emergency relief materials in order to expedite delivery to individuals impacted by a disaster. Günneç and Salman (2007) presented a two-stage multi-criteria stochastic programming model for a multi-facility location problem in pre-disaster planning for effective post-disaster emergency logistics. Ukkusuri and Yushimo (2008) presented a model incorporating the idea of the most reliable path in a facility location problem used in solving the inventory pre-positioning problem for humanitarian supply chains. Balcik and Beamon (2008) and Rawls and Turnquist (2010) created an optimization model, whose solution provides a prepositioning strategy for facility locations and inventory decision under uncertainty. The mathematical models determine the number and locations of distribution centers in a relief network and the amounts of relief supplies to be stocked at each distribution center. Recently, Irohara et al. (2013) proposed a tri-level programming model for disaster relief planning: the top level addressed facility location and inventory decisions, the second level represents damage caused by the disaster, and the third level which determines response and recovery decisions.

The distribution of relief supplies is another important aspect in disaster supply chain systems, especially in the post-disaster stage. When a disaster strikes, large volumes of emergency aid supplies must be made available immediately. The need for communities to have reliable, high-quality systems that are able to dispatch the correct quantities of relief supplies from distribution centers to the appropriate affected areas in a timely manner. Optimization models are developed as distribution models that are primarily applied to post-disaster scenarios. For example, Sheu (2007) presented a hybrid fuzzy clustering optimization approach to the emergency logistics co-distribution operations responding to urgent relief demands during the crucial rescue period. Tzeng et al. (2007) constructed a relief-distribution model using the multi-objective programming method for designing relief delivery systems in a real case. Yi and Özdamar (2007) proposed a mixed-integer multi-commodity network flow model that treats vehicles flows for coordinating logistics support in disaster response activities. Likewise, Ji and Zhu (2012) and Afshar and Haghani (2012) developed an optimization model describing integrated logistics operations in response to disasters.

This research is most closely related to that of Balcik and Beamon (2008), and aims at integrating decisions on both location and inventory simultaneously. However, one major difference is that the proposed model does not allow for unmet demand by modifying the constraint of the proportion of satisfied demand. Shortages and delays in a relief supply chain system can lead to more pain and suffering by survivors or other affected people. Unlike a commercial system, the budgets for relief systems are generally acceptable for unmet demand. Another important difference is that our model is used to determine the exact level of investment for a humanitarian organization. It is very difficult to predict the characteristics of a disaster, which can affect the investment budget, based on limited historical data. A system may sometimes require a large or a lower budget depending on how impactful the disaster is. If the investment can be estimated, we can determine the response by varying the budget, although evaluation is usually not possible ahead of time. Thus, this study attempts to provide a comprehensive model in order to satisfy the total relief demand by minimizing the logistics operations cost. We propose a strategic model that determines the locations of distribution centers and the total amount of pre-positioned inventory for each distribution center. Specifically, we apply the proposed model to the case of a flood in Thailand in order to demonstrate the advantages of assisting humanitarian agencies in making more precise decisions.

2. STATEMENT OF THE PROBLEM

In this study, we attempt to construct an efficient relief logistics system for the case of disaster incident, which is a major task for aid organizations. The basic goal of such relief efforts is to minimize the pain and suffering of victims when a disaster strikes. Identifying the location of relief distribution centers (points of origin) and affected areas (demand points) is a crucial task. Moreover, deciding the stock inventory for each relief item, such as food, water, medical supplies, and clothing, as well as how to rapidly and effectively dispatch these relief items from the different points of origin to destinations in the affected areas is of vital importance.

It is difficult for relief supply chain to obtain the reliable information of demand. However, there are ongoing studies to help assess global disaster and hazard risks in the relief surroundings. Van Westen (2013) indicates several aspects which should be evaluated in a hazard assessment: 1) the triggering event; 2) the areas where hazards are likely to initiate; 3) the areas where the hazards are likely to spread; and 4) the expected intensity of the hazard and its associated frequency or probability of occurrence. Balci and Beamon (2008) and Dilley et al. (2005) identify high-risk geographical areas, based on historical worldwide disaster frequency and mortality data, population data and economic indicators. Furthermore,
Hazus software is a natural hazard loss estimation software by the Federal Emergency Management Agency (FMEA) which can evaluate damages from potential disasters. The logistics cost of the relief system, of course, depends on the locations of facilities and the relief inventory quantity. Therefore, the accurate forecasts on potential demand locations and quantity inevitably influence the effectiveness of decision. In this study, we investigate the information of disaster locations and demand quantities by the historical data on frequency of disaster, population density and economic damage suffered as a result of catastrophe.

According to the principle on the facility location, each demand is ordinarily satisfied by the closest facility or warehouse if facility has unlimited capacity. In the realistic, however, there is the capacity limit for each warehouse. Moreover, the relief system thoroughly involves with the massive demand which able to exceed the supply capacity. Thus, we compare the experiment results of relief logistics between the model with capacity constraint and the unlimited capacity model. The model also consider the restriction on response time in the network in order to react with the rapid relief chain. Next, we present the mathematical model formulation of this problem.

3. PROBLEM ASSUMPTIONS

The research questions are to determine the relief distribution chain for flood disaster consisting of the candidate warehouses and the amount of relief items to be delivered to each demand point in the affected area. We have several assumptions for the model as follows.

3.1 Warehouses

According to the response stage of disaster management system, all warehouses are already preexisting and prompt to be operated. Thus, we consider the operational cost for opening a warehouse rather than the establishing cost in this problem. All warehouses have the same capacity but can be categorized as having a high opening cost or a low opening cost (Appendix). This also leads to holding costs for relief items since staff must be employed for the purpose.Warehouses with high opening costs could include local government office buildings, which have higher operation costs for both opening and holding. On the other hand, low opening cost warehouses may include, for example, temples, which involve greater participation by volunteers.

3.2 Response Time

We consider the transportation cost between each warehouse and demand point as the response time, rather than the distance for dispatch commodities among both of them. The reason for this is that a number of the characteristics of the relief logistics system will be adjusted in the event of a disaster, for example, many roads and highways are inundated with water during a flood. Thus, we are unable to use the transport distance data in this relief effort problem. We also assume that the transportation routes are the same with normal traffic between each path of warehouses and demand points but the vehicles will take longer time than normal by car because of the obstacle of water. In the current case study, truck and boat will be used for transporting the relief items to each demand point. Multiplying the constant coefficient given by the specialist of the case study (Department of Disaster Prevention and Mitigation [DDPM] of the Royal Thai Government) with the actual time for normal traffic (by car) is able to represent the response time (by truck and boat) for each route of this current problem. Figure 1 displays the response time operated for distributing items between warehouses to demand points. In this problem, each warehouse delivers relief items to various demand points while each demand point is able to receive items from multi facility as well. Let $t_i$ is response time to satisfy demand point $i$ from warehouse $j$.

4. MODEL FORMULATION

The mixed integer programming (MIP) formulation can be written in terms of the following notations:

**Index Sets:**
- $I$ set of demand points in the affected areas
- $J$ set of candidate warehouses
- $K$ set of relief item types

**Variables:**
- $q^k_j$ units of item type $k$ to be stored at warehouse $j$
- $z^k_j$ proportion of item type $k$ satisfied by warehouse $j$ that provides service to demand point $i$
- $x_j = 1$, if warehouse $j$ is opened,
- $x_j = 0$, otherwise;
\[ y_{ij} = \begin{cases} 1, & \text{if warehouse } j \text{ provides service to demand point } i, \\ 0, & \text{otherwise; } \end{cases} \]

Parameters:
- \( d_{ik} \): expected demand for item type \( k \) at demand point \( i \)
- \( c_j \): capacity of warehouse \( j \)
- \( v_k \): unit volume of each item type \( k \)
- \( f_j \): fixed cost of opening warehouse \( j \)
- \( h_{kj} \): unit cost of storing item type \( k \) at warehouse \( j \)
- \( s_{kj} \): unit cost of shipping item type \( k \) to demand point \( i \) from warehouse \( j \)
- \( t_g \): response time to satisfy demand point \( i \) from warehouse \( j \)
- \( r_i \): maximum response time limit to perform at demand point \( i \)

Based on the above definitions, we developed the following MIP formulation:

\[
\begin{align*}
\text{minimize} & \quad \sum_{j \in J} f_j x_j + \sum_{k \in K} \sum_{j \in J} h_{kj} y_{ij} + \sum_{k \in K} \sum_{j \in J} \sum_{i \in I} s_{kj} d_{ik} z_{ikj} \\
\text{subject to} & \quad \sum_{j \in J} z_{ikj} = 1, \quad \forall i \in I, \forall k \in K \quad (2) \\
& \quad z_{ikj} \leq y_{ij}, \quad \forall i \in I, \forall j \in J, \forall k \in K \quad (3) \\
& \quad \sum_{k \in K} \sum_{j \in J} v_k q_{kj} \leq c_j x_j, \quad \forall j \in J \quad (4) \\
& \quad \sum_{i \in I} \sum_{j \in J} d_{ik} z_{ikj} \leq q_{kj}, \quad \forall j \in J, \forall k \in K \quad (5) \\
& \quad t_g y_{ij} \leq r_i, \quad \forall i \in I, \forall j \in J \quad (6) \\
& \quad y_{ij} \geq x_j, \quad \forall i \in I, \forall j \in J \quad (7) \\
& \quad 0 \leq z_{ikj} \leq 1, \quad \forall i \in I, \forall j \in J, \forall k \in K \quad (8) \\
& \quad x_j, y_{ij} \in \{0,1\}, \quad \forall i \in I, \forall j \in J \quad (9)
\end{align*}
\]

The objective function (1) minimizes the sum of the total costs of relief operations corresponding to the costs of opening warehouses and the holding costs and shipping costs of relief items. Constraint (2) stipulates that each demand point is fully assigned, whereas constraint (3) states that demand can only be serviced by warehouse which is assigned to the demand point. Constraint (4) ensures that the amount of inventory that is maintained at any warehouse does not exceed the capacity of that warehouse. Constraint (5) ensures that the inventory level at a warehouse is no smaller than the demand at each demand point. Constraint (6) requires that the expected time to satisfy the demand be no longer than the maximum response time, and constraint (7) ensures that warehouse can provide service when it is opened. The non-negativity constraint (8) indicates the proportion of demand that is satisfied. Finally, constraint (9) defines the binary variable for the warehouse location and the service path.

5. **NUMERICAL EXPERIMENTS**

5.1 **Data Sets**

In this section, we demonstrate the applicability of the mathematical model presented by conduction a case study of Thai flood which is one of the most significant disaster problems in the world (The World Bank, 2012). Over the past three decades, floods resulting in more than ten deaths have occurred 224 times and an average of 5.2 million people have been effected each year (DDPM, 2012). One of the most critical provinces (from the total of 77) in terms of population density and economic damage suffered as a result of annual flooding is considered in the present study. We investigate historical data for inundated areas in this critical province as provided by the DDPM. Based on this flood location database, we can depict the parameters related to demand locations in the relief logistics problem by considering areas having a high frequency of flood disasters. The actual data on the affected population and number of households are considered to be the demand quantity. All warehouses stock and distribute multiple types of relief item. Relief items in this system are distributed to the hands of the aid recipients in the form of emergency aid packages. Two types of aid packages are considered. The first type satisfies individual demands, whereas the second satisfies the demands of a number of affected households. Finally, the formulated problem involves 47 demand points and 13 candidate warehouses shown in Figure 2.

5.2 **Computational Results**

In this section, the computational results and analysis of the proposed model behavior are presented. The optimal solutions were obtained using Gurobi optimizer version 5.6.2 mathematical programming solver. All experiments were run on a personal computer with an Intel Core...
i7-3770 CPU (3.40 GHz) and 16.0 GB of RAM. All test problems were computed in less than one second.

Next, we present illustrative examples in order to demonstrate how the proposed models can be used to optimize the facility locations and stock decision. The example result refers to the solution of one area from the total average of 50 areas have been flooded each year for this case study. In order to assist an aid agency in making more effective decisions in a relief effort, Figure 3 shows how the maximum response time at each demand point affects the total cost (objective function) and all three types of operation costs considered. At first glance, the gradual increase in the maximum response time appears to reduce the total operation cost. This means that budget limitations can lead to a slow response system. According to this sample data set, the formulated system is unable to distribute supplies if the time restriction is less than 170 minutes for each demand point. The objective function, on the other hand, is unchanged when the system has more than 320 minutes according to the same performance of each response result.

Second, both the opening cost of the warehouse and the holding cost exhibit similar trends as the objective function. On the other hand, only the shipping cost increases when the maximum response time increases. This implies that, for a case in which the constraints are more restrictive, the relief system must open more warehouses in order to provide timely service for each demand point. Thus, each affected area is likely to be serviced by a closer warehouse because several warehouses are opened. Several high cost warehouses are selected in the restrictive situations because they are showing the higher holding cost than in the relaxed situations. In contrast, the system opens fewer warehouses when the time constraint is loosened. The transportation expense tends to increase due to the longer distances between warehouses and demand points. Moreover, the impacts to the system of those three types of cost are quite competitive in this case study. It can be seen that total shipping cost is higher than total opening cost in the relaxed systems while it represents the contradiction in the restrictive situations.

Figure 4 is displayed to give more clear of picture results on the logistics cost apportionment with capacity constraint. The maximum response time \( r_j \) has been differently set to 170 and 300 minutes to indicate the distinct characteristics of the performance results. The percentages of utilization are also shown with each warehouse. In the serious condition \( (r_j = 170) \), ten of candidate warehouses are used for providing the service on short time while the system opens seven warehouses in the less serious condition \( (r_j = 300) \). It can be seen that the system attempt to open the low cost warehouse rather than the expensive ones. Although, it is inevitable to include the selection of high cost warehouse in the serious system \( (r_j = 170) \) if we prefer to make a rapid response to the affected victims. Additionally, in term of the effectiveness of warehouse capacity, the relaxed system performs better than the serious system according to the percentage of utilization.

However, some of demand points are not connected to the nearest warehouse in Figure 4 because of two reasons. First is that facility already reaches the maximum holding. Second is that both opening cost and holding cost is higher than the shipping expense in this problem. For example, the strict system \( (r_j = 170) \) in Figure 4 displays that some demand point receives the shipment from warehouse 8 instead of warehouse 6 which is closer to its location and still has more left capacity. This is because holding supplies in the expensive warehouse with shorter transport will cost higher than holding them in the low

![Figure 3. Results for the objective function, opening cost, holding cost, and shipping cost under the maximum response time.](image-url)
cost warehouse with longer shipment. As we mention earlier, the structure of the cost formulation of this current study is quite competitive. Thus, selecting the far-located low cost warehouse and near-located high cost warehouse is the trade-off problem between opening cost and shipping cost.

Furthermore, Figure 5 depicts the experiment results when the system has unlimited capacity to stock. Each demand point is connected to its closest warehouse when we loosen the constraint on capacity. However, the same ten warehouses from the limited capacity constraint in the serious system \( r_i = 170 \) are opened in order to provide the quick services with short distances while the relaxed system \( r_i = 300 \) opens only two warehouses. The result should open only one warehouse because of no restriction on capacity but the total longer transport will cost greater instead. Therefore, the optimal solution for this unlimited capacity condition is to open two low cost warehouses in this problem.

The result for the response time for each demand point is another important consideration regarding the maximum response time. Figure 6 illustrates the fluctuation of the response time performance between 200 and 300 minutes. As mentioned earlier, the greater the maximum response time of the system, the lower the logistics expense the aid agency pays. However, the more restricted the maximum response time, the better the emergency logistics performance, as indicated by the lower average value of \( t_{ij} \). Thus, the pain or suffering is likely to be significantly lower for \( r_i = 200 \) minutes than for \( r_i = 300 \) minutes. Not only for average response time but also standard deviation are lower in the serious system. Standard response time result deviations shown in \( r_i = 200 \) minutes perform better than in \( r_i = 300 \) minutes. This could be implied about the service equity or balance which is another important aspect for the humanitarian relief chain because the ability to deliver equal levels of service to every demand point is a standard requirement placed on official aid agencies. Lastly, we concern the fluctuation in the performance of \( t_{ij} \). The operational performance of the relaxed system appears to fluctuate more than that of the strongly restricted system, as shown in Figure 7. The linear trend of mean and standard deviation of \( t_{ij} \) are also plotted as the dashed lines. Not only the rapidity but also the balance, this characteristics of outcome indicates that the relax system is less well-perfor-
med than the more serious one. Each demand in the higher relax condition is likely to be satisfied with more imbalance. The gradual increase in the relaxation of the time constraint may lead to an unfair supply distribution in terms of rapid response. Some affected areas may be supplied very rapidly, whereas other areas may receive aid slowly. Moreover, the decision maker can consider the funding to allocate in advance by concerning the cost effectiveness in Figure 3 with the outcome of quick response and service equity of the system in Figure 7. The objective function of cost ratio in the restrictive situations ($r_i = 170$ to $r_i = 230$) is greater than the cost slope of the relax systems ($r_i = 240$ to $r_i = 320$). By considering the result of average quick response and service equity for the relief system, the cost effectiveness helps agency to determine budgetary management much more productively.

5.3 Current Problem-to-Solution Findings

As stated earlier, this case study is faced with flooding almost every year. However, in the reality of this problem, many time there are errors and inefficient performance issues including improper opened warehouses, overstock or shortage situations, delays, etc. An overview of the current major problems is as follows:

- All warehouses are requested to open and stock multiple commodities every time the city is encountered by flooding. However, since experiments show that total demand can be satisfied by opening certain selected warehouses from the total available, many warehouses will have ineffective inventory utilization.
- The decided stock and distribution from opened warehouses to each demand point are issued in the form of...
commands from the central office, which sometimes lacks communication links with and accurate information on the affected areas. This almost always results in shortage and overstock situations, as well as relief distribution delays.

In this case study, we determined that our proposed models are capable of narrowing down relief logistics system performance deficiencies and that with preparedness improvements the government could provide more efficient responses, and thus minimize the pain and suffering of disaster victims.

6. CONCLUSIONS

Emergency logistics, as a complement to the current strategy of relief supply chain system, has several advantages for humanitarian organizations, including higher efficiency of procurement of relief supplies, improved response time, and lower shipping costs, as indicated by the results of the proposed model, which show how the humanitarian system can be used to optimize the best investment in order to achieve the highest possible benefit in terms of emergency logistics. Moreover, these advantages support the implementation of the distribution network described hereinafter. The proposed model estimates the frequency, location, and magnitude of the potential demand based on historical data and optimizes the locations of warehouses and inventory allocation under time restrictions in terms of the number of warehouses to be opened and amounts of inventory to be stored.

The present research is most closely related to that of Balcı and Beamon (2008), and aims at integrating decisions on both location and inventory. However, the amount of unmet demand is acceptable in their model. Therefore, one advantage is to eliminate the dissatisfaction of the victims. By modifying the constraint on the proportion of satisfied demand, the result no longer allows the unmet demand. Based on the relief supply principle and the government policy, any shortage or delay should be eliminated. Otherwise, the pain and suffering of affected people may increase. Another important advantage is that the DDPM determines the desired configuration of the relief network and provides a roadmap of how to appropriately allocate funds toward this goal as they become available. By clarifying the advantages with respect to the performance and overall configuration of the network, the DDPM can reduce their initial options within each area and consider other criteria, such as the stability of the candidate location, the cost of warehouses, labor costs, customs regulations, the political situation, logistics accessibility, and the potential for collaboration with other agencies in making final decisions. However, there would be more advantages and insights from the research experiments when the investigations on multi case studies or problems are applied. In the future research, we intend to enlarge the comparison considered on many cases of disaster reliefs.

There are a number of possible extensions of this model. Vehicle routing and scheduling provide a significant opportunity for improving the flow of the relief distribution network. In particular, in the case of flooding, the most common transport channels are trucks in unaffected areas and boats in affected areas. Future research will focus on developing a more sophisticated vehicle routing and scheduling system to address the relief response stage after a disaster has struck. Evacuation plan is also very important for disaster preparedness. In this study, we do not consider the evacuation in the formulation model according to the feature of the problem. However, if the disaster becomes greater and more crucial, affected people in the disaster zone have to be evacuated to shelters. Lastly, in the present study, we assumed that disasters do not strike concurrently and that distribution centers have sufficient inventory to satisfy the demand for any example problem, based on publicly available disaster data. This can lead to more efficient stocking policies for relief efforts. Thus, the present research will become more practical as the logistics attributes of facility location, distribution network, and inventory management, are further integrated.

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### Appendix

**Table A1. Supporting data of warehouse information**

<table>
<thead>
<tr>
<th>Warehouse type</th>
<th>Warehouse number</th>
<th>Opening cost (THB)</th>
<th>Holding cost per unit (THB)</th>
<th>Maximum capacity</th>
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<td>Low cost</td>
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<td>500,000</td>
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**Table A2. Supporting data of demand information**

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<th>Demand Item 2</th>
<th>Demand Item 1</th>
<th>Demand Item 2</th>
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