

Integrated Relief Supply Distribution and Evacuation: A Stochastic Approach

Wapee Manopiniwes and Takashi Irohara

Abstract This chapter presents a stochastic optimization model for disaster management planning. In particular, the focus is on the integrated decisions about the distribution of relief supplies and evacuation operations. The proposed decision-making approach recommends the best relief distribution centers to use as storage locations and determines their optimal inventory levels. The model also incorporates the priorities for the evacuation of particular communities, as well as specific disaster scenarios with estimates of the transportation needs and demand for aid. A case study is presented to determine the distribution of aid for a flood emergency in Thailand that uses a flood hazard map.

Keywords Facility location · Stochastic · Humanitarian logistics · Disaster relief

1 Introduction

Humanitarian logistics is central to disaster relief. In both rapid- and slow-onset disasters or emergencies, it is necessary to procure and move the required material (water, food, shelter, clothing, medicines, and other supplies) from storage locations to appropriate destinations in the affected area and to do this in the most efficient and effective way possible. It can thus be argued that the logistic capabilities required by aid agencies and others who deal with large scale, sudden-onset disasters, are similar to those required by commercial organizations. In a previous study (Manopiniwes et al. 2014), we described a situation in which decisions were based on a deterministic model in which a flood or other catastrophe could occur. However, humanitarian logistics can be defined as the ability to respond rapidly to unexpected changes in demand or supply conditions. Therefore, in this study, we introduce a stochastic approach for planning the storage and distribution of

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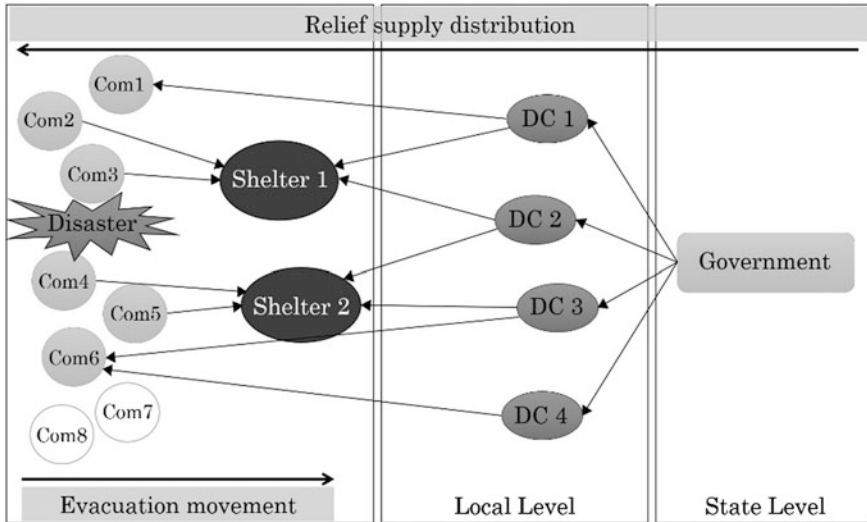


Fig. 1 Supply chain management for disaster relief

emergency aid packages in a flood disaster. We also consider how to make integrated decisions about the evacuation of various communities.

Our stochastic model provides a decision-making model for the preparedness stage of a disaster management system, and it considers the outcomes of the various possible responses. While past researches had considered supply distribution and evacuation process separately, we connect both planning contexts as the integrated decision as summarized in Fig. 1 corresponding not only to the demand at evacuation shelters but also to people who remain in the affected area. Our method is able to recommend which of the candidate distribution centers (DCs) will be the best storage locations and to determine appropriate inventory levels. The model incorporates the priorities of evacuating particular communities, as well as specific disaster scenarios, with transportation and demand estimates.

The remainder of this chapter is organized as follows. In Sect. 2, we provide an overview of the existing literature. Section 3 presents our stochastic approach to disaster preparedness, and Sect. 4 presents a case study of a flood disaster in Thailand. In Sect. 5, we evaluate and analyze the results of our approach, and finally, in Sect. 6, we summarize our contributions and discuss directions for further research.

2 Literature Survey

According to the steep increase in the number of articles on relief supply chain management in recent years, a broad overview of the issues is addressed ranging from a principle or conceptual framework to the analytical methodology and case

study applied. Among a number of distributions in this field, the Operations Research (OR) encompasses the most objective challenges. Therefore, articles surveying disaster supply chain papers include an OR methodology survey by Altay and Green (2006) and a review of relief supply chain optimization by Manopiniwes and Irohara (2014). Most articles dealing with disaster supply chain are focusing either on the distribution of relief supplies or on the evacuation movement.

2.1 Stock Prepositioning and Distribution Management

There are many papers dealing with stock prepositioning and distribution management. Barbarosoglu and Arda (2004) offered a multi-modal network flow to plan the transportation of vital first-aid commodities to disaster-affected areas during emergency response. Jia et al. (2007) proposed models and solution approaches for determining the facility locations of medical supplies in response to large-scale emergency. The study is to investigate which facilities should be opened and the order in which facilities are opened can have a significant effect on the quality of coverage. 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 the distribution center in relief network and the amount of relief supplies to be stocked at each distribution center. Irohara et al. (2013) proposed a tri-level programming model for this integrated category. The top level addressed facility location and inventory decisions; the second level represents damage caused by the disaster, while the third level determines response and recovery decisions. A recent paper by Abounacer et al. (2014) presents a multi-objective location-transportation problem for disaster response aims at determining the number, the position, and the mission of required humanitarian aid distribution centers within the disaster region. Salman and Yücel (2015) propose an emergency facility location to maximize the expected demand coverage within a specified distance over all possible network realizations.

2.2 Sheltering and Evacuation Operations

We have also found several papers considering on evacuation operations. Kongsomsaksakul et al. (2005) studied the optimal shelter locations for the flood evacuation planning. They formulated a bi-level programming model for determining shelter locations with the upper level and traveler behavior with the lower level. Another bi-level optimization model was proposed by Liu et al. (2006) for optimal evacuation planning: The high level tries to maximize the throughput in the target evacuation clearance time, whereas the low level is to minimize total

clearance time. Song et al. (2009) presented an optimization modeling technique to develop an evacuation plan for transit-dependent residents during the hurricane evacuation. Most recent work with respect to natural disasters has focused either on evacuation strategies or the distribution of relief supplies. Recently, article by Kelle et al. (2014) proposed the integrated evacuation and resource allocation which the decision criterion is to find the appropriate compromise between the worst-case and average cost consideration. While their paper is based on the assumption that all affected people are evacuated to some facilities, our current study formulates the integrated decision of evacuation and relief supplies distribution corresponding not only to the demand at evacuation shelters but also to the people who remain in the affected area.

2.3 Stochastic Programming

Stochastic programming is one of the most widely used tools for planning in the preparedness stage (Altay and Green 2006) due to its ability to handle uncertainty by probabilistic scenarios representing disasters and their outcomes (Barbarosoglu and Arda 2004; Balcik and Beamon 2008; Rawls and Turnquist 2010; Salman and Yücel 2015; Song et al. 2009; Kelle et al. 2014). The flood emergency logistics preparation problem with uncertainty is formulated by Chang et al. (2007) as two stochastic programming models that allow for the determination of a rescue resource distribution system for urban flood disasters by applying the data processing and network analysis functions of the geographic information system. Flooding potential maps can estimate the possible locations of rescue demand points and the required amount of rescue equipment. Mete and Zabinsky (2010) developed a stochastic model for the location and delivery of medical supplies in Seattle area with regard to the earthquake disaster. The randomness in the location and amount of demand, and in the available transportation routes and transportation times leads to different types of scenarios where the transportation routes and times are directly related to the location and amount of demand. Lately, Verma and Gaukler (2014) evaluated the performance of two models between deterministic and stochastic modeling approaches using large-scale emergencies caused by an earthquake in California. They found that the locations suggested by the stochastic model significantly reduce the expected cost of providing supplies. They also demonstrate that the cost advantage of the stochastic model over the deterministic model is especially large when only a few facilities can be placed.

Our study makes the following contributions: provides the new approach modeling for the integrated decision on the evacuation planning and relief supplies distribution for floods emergency response. With the stochastic formulation based on the flood hazard map, the value of decision performance is particularly great in a large-scale realistic with budget-constrained situations.

3 Proposed Integrated Stochastic Model

In this section, we formulate the model for disaster preparedness decision making, with consideration of the expected outcomes of the response stage. The decisions that are made before a disaster hits are usually made with consideration of all possible scenarios, while decisions that are made afterward must depend on the actual scenario. To allow for this uncertainty, we calculate the expected costs for each of several scenarios. Stochastic programming allows for several different decisions to be integrated.

Pre-disaster decisions:

- The selection of the locations of the local relief DCs, which are to be used for receiving the relief supplies from the state level and dispatching them to the demand points
- The inventory of relief supplies to be stored at each DC

Scenario-specific post-disaster decisions:

- The distribution assignment for each DC, such that relief supplies are delivered to the demand destinations, which include shelters as well as communities that have not been evacuated
- The evacuation operations for moving each affected community to the assigned shelters.

Let I be the set of communities in the affected area, J be the set of candidate DC locations, L be the set of possible shelters, and the scenarios be denoted $\omega \in \Omega$ in the formulation of the model.

Pre-disaster decision variables:

m_j amount of relief supplies to be stored at DC j

x_j

$$: \begin{cases} = 1, & \text{if DC } j \text{ is opened,} \\ = 0, & \text{otherwise;} \end{cases}$$

Post-disaster decision variables:

$q_{ij}^C(\omega)$ quantity of relief supplies satisfied by DC j that provides service to community i for scenario ω

$q_{ij}^S(\omega)$ quantity of relief supplies satisfied by DC j that provides service to shelter l for scenario ω

$e_{il}(\omega)$ total evacuees moved from community i to shelter l for scenario ω .

Pre-disaster parameters:

c_j capacity of DC j ;

a unit volume of relief supplies;

f_j opening cost of DC j ; and

g_j^D unit cost of shipping relief supplies to DC j from state level.

Post-disaster parameters:

$d_i(\omega)$ demand of relief supplies at community i for scenario ω ;

$g_{ij}^C(\omega)$ unit cost of shipping relief supplies to community i from DC j for scenario ω ;

$g_{lj}^S(\omega)$ unit cost of shipping relief supplies to shelter l from DC j for scenario ω ;

$g_{il}^E(\omega)$ transportation cost to evacuate one person from community i to shelter l for scenario ω ; and

$\text{prob}(\omega)$ probability of occurrence of disaster scenario ω .

The mixed-integer stochastic programming formulation is given as:

$$\text{minimize } \sum_{j \in J} f_j x_j + \sum_{j \in J} m_j g_j^D + E_{\Omega}[Q(x_j, m_j, \omega)] \quad (1)$$

subjected to

$$E_{\Omega}[Q(x_j, m_j, \omega)] = \sum_{\omega \in \Omega} \text{prob}(\omega) Q(x_j, m_j, \omega) \quad (2)$$

$$Q(x_j, m_j, \omega) = \sum_{i \in I} \sum_{l \in L} g_{il}^E(\omega) e_{il}(\omega) + \sum_{i \in I} \sum_{j \in J} g_{ij}^C(\omega) q_{ij}^C(\omega) + \sum_{l \in L} \sum_{j \in J} g_{lj}^S(\omega) q_{lj}^S(\omega) \quad \forall \omega \in \Omega \quad (3)$$

$$a m_j \leq c_j x_j \quad \forall j \in J \quad (4)$$

$$\sum_{i \in I} q_{ij}^C(\omega) + \sum_{l \in L} q_{lj}^S(\omega) \leq m_j \quad \forall j \in J, \forall \omega \in \Omega \quad (5)$$

$$\sum_{j \in J} q_{ij}^C(\omega) = d_j(\omega) - \sum_{l \in L} e_{il}(\omega) \quad \forall i \in I, \forall \omega \in \Omega \quad (6)$$

$$\sum_{j \in J} q_{lj}^S(\omega) = \sum_{i \in I} e_{il}(\omega) \quad \forall l \in L, \forall \omega \in \Omega \quad (7)$$

$$q_{ij}^C(\omega), q_{lj}^S(\omega), e_{il}(\omega) \geq 0 \quad \forall i \in I, \forall j \in J, \forall l \in L, \forall \omega \in \Omega \quad (8)$$

$$x_j \in \{0, 1\} \quad \forall j \in J \quad (9)$$

Optimization (1) is to minimize, as the objective function, the cost of opening each DC, the cost to ship relief supplies from state level to each DC, and the expected cost of the response stage for each disaster scenario. The expected cost of

the response stage is expressed by Eq. (2), where, for each scenario, the cost of the response stage includes the cost of transporting evacuees and the cost of shipping relief supplies from the DCs to the demand destinations (communities and shelters), as shown in constraint (3). Constraint (4) ensures that the amount of relief supplies maintained at any DC does not exceed the capacity of that DC, whereas constraint (5) states that the combined supply stock at the DCs is not less than the total demand of both the communities and the shelters. Constraint (6) ensures that the amount of relief supplies shipped from a DC to a community be equal to the demand that remains after any residents are evacuated. In addition, constraint (7) ensures that all evacuees at shelters receive relief supplies from a DC. The non-negativity constraint (8) indicates the number of shipments of relief supplies, and constraint (9) is a binary variable for each DC location.

However, we note that the cost of opening the shelters is not considered in the model formulation, because these are usually preexisting building, such as stadiums, and they are only temporarily used as evacuation shelters. Therefore, in this model, we assume that there is no opening or operating cost for the shelters.

4 Case Study of a Flood in Thailand

This section presents a case study regarding to the preparation and response to flood disaster in Chiang Mai Province in northern Thailand. Infrequent large floods usually occur in northern Thailand late in the May–October rainy season which is dominated by masses of moist air moving northeast from the Indian Ocean associated with tropical depressions moving westward from the South China Sea (Wood and Ziegler 2008).

Chiang Mai developed an early flood warning system which is able to detect by the real-time situation of Ping River as the gauging station P.1. When there is a heavy rainfall, it is able to evaluate the flood impact in the downtown by the level of Ping River at station P.1. In this study, we generate the possible scenarios for the need of relief supplies following to Chiang Mai flood hazard map studied by Civil Engineering Chiang Mai University Natural Disasters Research Unit: CENDRU (2015) as shown in Fig. 2. The flood hazard map is the analysis of different flooding risk area based on the historical data of station P.1 which can be constructed as 7 impact levels.

Using our stochastic approach, we used the flood hazard map for Chiang Mai to generate disaster scenarios that closely match real floods in this area. We considered seven different scenarios, and their probabilities of occurrence are calculated from historical data for the past three decades: 0.35, 0.20, 0.18, 0.12, 0.08, 0.05, and 0.02 for scenario 1–7, respectively. Each of these scenarios creates a different demand for relief, depending on how much of the area is affected.

Relief supplies are as identical as aid packages. We consider six possible relief DCs, two possible shelters, and sixteen communities with estimated demand amount at communities from the number of population record. Figure 3 marks the

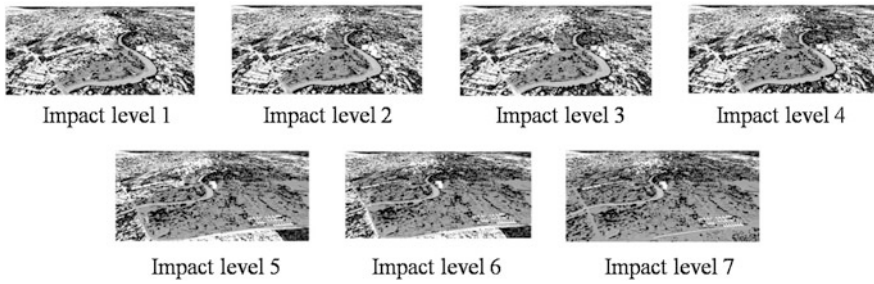


Fig. 2 Seven levels of Chiang Mai flood hazard map (CENDRU 2015)

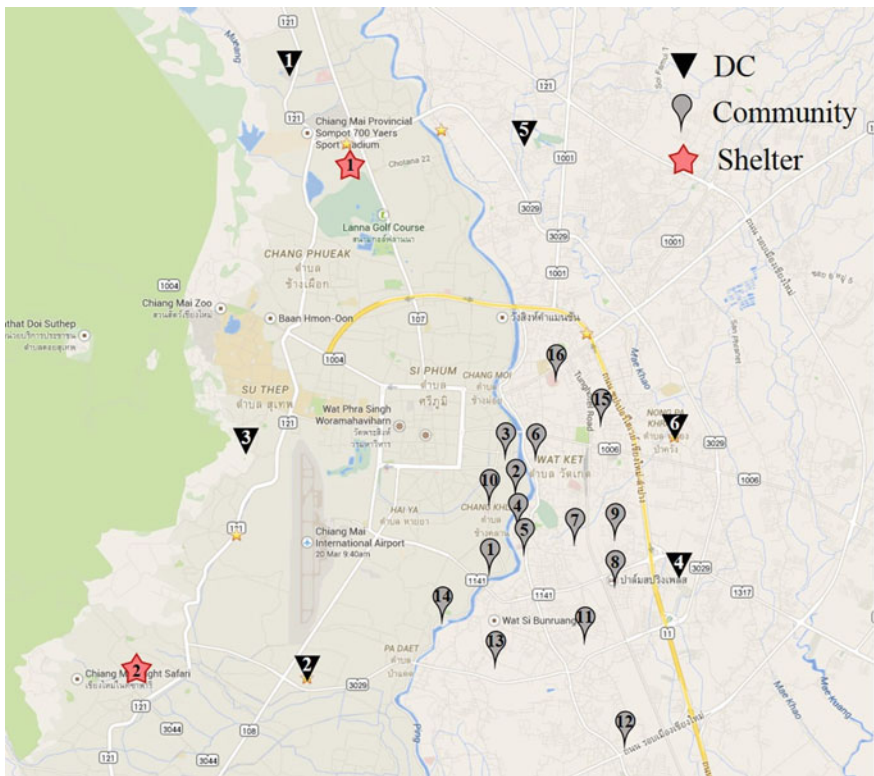


Fig. 3 Locations of affected communities, possible shelters, and relief DCs

locations of DCs, shelters, and communities given in this study. The transportation times for each scenario are determined by considering the effect of flood impact level. For example, the same route between DC 4 and community 1 does not take equal transportation time for distributing the relief supplies in each scenario. Transportation time is getting longer in the more severe impact level.

5 Computational Results

We solve the stochastic model using Gurobi Optimizer Ver. 6.0.0 mathematical programming solution software. All experiments were run on a personal computer with an Intel (R) Core (TM) i7-3770 CPU (3.40 GHz) and 16.0 GB of RAM. All the runs solved in less than 1 min.

The optimal solution to the stochastic model selected three relief DCs (2, 3, and 4) for storing emergency aid packages in preparation for a possible flood. The primary reasons that these locations were selected were their capacities and their distances from the communities and shelters. The opening cost and capacity of each DC were the same. For a successful storage plan, the total expected demand, which is based on the various possible scenarios, requires at least three relief DCs. On the left side of the Ping River, DCs 2 and 3 were chosen because they are closest to the demand destinations, not only the communities likely to be affected but also the evacuation shelters. DC 4 was chosen over DCs 5 and 6 to serve the communities on the right side of the Ping River.

We also calculated the results with the addition of one more constraint (10), which

$$\sum_{j \in J} x_j = k \quad k \in \{1, 2, 3, 4, 5, 6\} \tag{10}$$

limits the total number for DCs selected; this was done in order to determine their relative importance. As stated earlier, the expected demand requires at least three DCs for storing the relief. When fewer than three DCs are allocated, it was necessary to increase their capacity; otherwise, there was no feasible solution. We increased the cost of opening a DC so that it would reflect the larger capacity, and this is consistent with realistic situations. Figure 4 shows the selected DCs; the total number of DCs ranged from one to six, as in constraint (10). We found that the selection of three DCs minimized the total cost. We note that DC 2 was the best potential location, and it was selected each time; DCs 4 and 3, respectively, were the second and third most frequently chosen.

Because the purpose of the model is to make integrated decisions about the distribution of supplies and about evacuations, the cost of shipping supplies and the evacuation costs are some of the most critical factors in this approach. Figure 5 depicts the experimental results when varying the cost per unit of evacuation and the shipping cost per unit of supplies. The solutions that are shown satisfy the objective function, and the combined cost of evacuation, shipping to communities, and shipping to shelters. The cost of opening DCs and the cost of shipping supplies from the state level to the DCs are not included in the solutions shown in the figure, because the DCs all had the same opening cost, and the cost of shipping from the state level will be almost constant, since the distances to the DCs are similar.

It is clear that the left side of the figure represents a lower cost per unit of evacuation, while the right side represents a lower cost for shipping a unit of

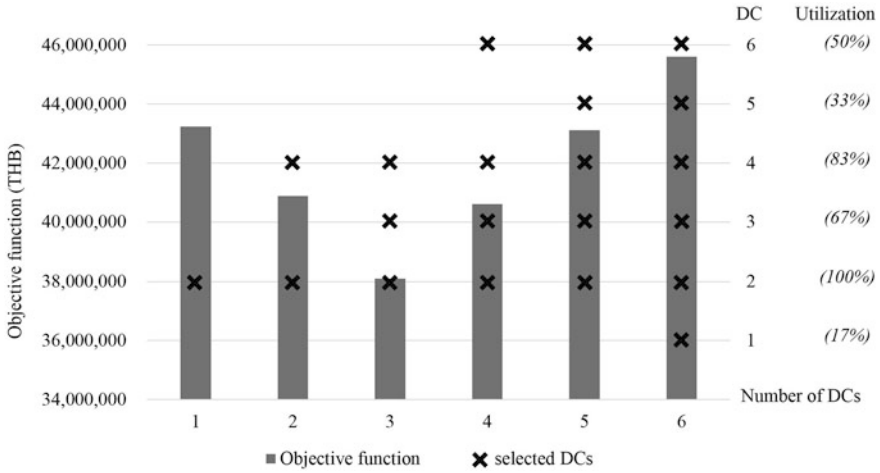


Fig. 4 Selection of relief DCs when the total number was specified

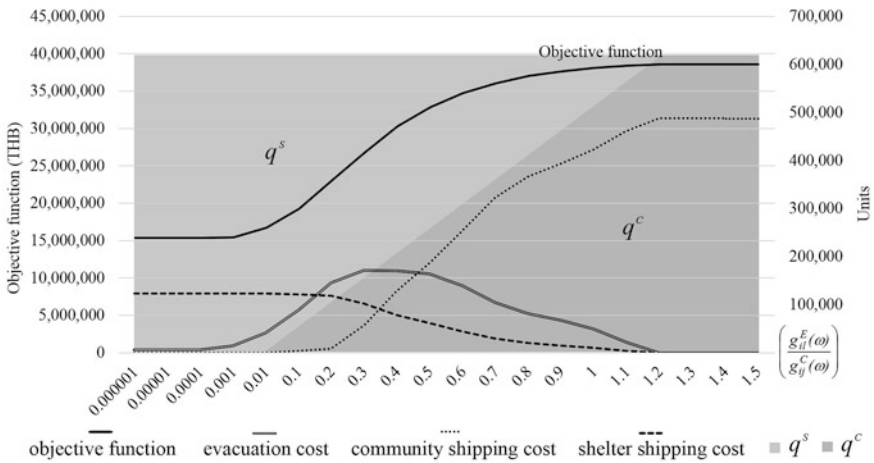


Fig. 5 Experimental results when varying the unit cost of evacuation and the cost for shipping a unit of relief supplies

supplies. Therefore, we can see that there is a steady increase in the amount of supplies shipped to shelters and evacuees when the unit cost of evacuation is significantly decreased. When the unit cost of evacuation is less, the model decides to evacuate more people from their communities to shelters, and thus more supplies have to be shipped to the shelters. The amount of supplies shipped to communities, on the other hand, increases when there is a higher cost per unit of evacuation; this continues until the unit cost of evacuation is 20 % higher than the unit cost of shipping supplies, and at that point, the model decides that everyone should remain

in their community. The costs of shipping to the communities and shelters are directly related to the amount of supplies that are shipped to each.

We note that the cost of evacuation is important. Everyone is evacuated to a shelter, until the unit cost of evacuation is a thousand times smaller than the unit cost of shipping supplies; this is because the unit cost of evacuation is very small. Evacuations peak when the unit cost of evacuation is one-third of the unit cost of supplies, and they continuously decrease until they reach zero, when the unit cost of evacuations is 20 % higher than the unit cost of shipping supplies. Finally, the solutions provide a better value for the objective function when the evacuation rate is higher. Higher evacuation rates indicate a higher demand at the shelters, which reduces the expense of shipping supplies, because the distance from the DCs to the shelters is less than the distance to the communities.

6 Conclusion and Future Research

The present study proposed a decision-making model for the disaster management planning, which incorporate making integrated decisions about the distribution of relief supplies and about evacuation operations. Our stochastic approach determines the best storage locations from among a set of possible relief DCs, and it also determines their inventory levels. The model is also able to incorporate the priorities for evacuating particular communities, as well as specific disaster scenarios with estimates of the transportation needs and demands for relief.

There have been many studies of disaster supply chains, focusing on the distribution of relief supplies or on the evacuation of residents. To the best of our knowledge, no previous disaster management study has integrated these two aspects. Our stochastic model uses information about the expected magnitude of disasters to provide the optimal policy for the location and inventory of relief DCs and shelters.

Our future research will focus on developing a more sophisticated method for routing vehicles and a better scheduling system for the response stage of disaster management. With the results that we have obtained in this study, we can create an aggregated transportation plan with a detailed plan for routing vehicles, determining their loads of emergency aid packages, and ensuring the demand is met at each of the shelters and communities.

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