Integrated humanitarian operations management in flood natural disaster

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Abstract

This study described a comprehensive model that characterizes integrated humanitarian operations management in response to natural flood disasters. The proposed model use a two-stage approach to account for all related emergency logistics operations in the preparedness and response phases of disaster cycle management. The first stage concerns preparedness and initial response decisions while the second stage has been developed as a decision-making support tool for underlying, problems that arise during the flood disaster response phase.

Keywords: Humanitarian Operations Management, Optimization, Floods

Introduction

According to the claims of climate scientists and the trend in disaster frequency during the recent decades as above, academicians have duly responded by developing mathematical models and solution algorithms that deal with different aspects of disasters. The field of knowledge on humanitarian logistics and supply chain management has attracted attention from a variety of stakeholders, such as scholars, practitioners and policy makers (Jabbour et al., 2017; Banomyong 2017). An emerging and imperative research area that is sustained by operations management (OM) scholars. While questions regarding the position of general or commercial logistics and supply chain have long been a topic of interest, much of the existing literature on humanitarian logistics management is quite fresh and still not enough. Latest data shows the global increase in natural disasters number which underlines the need for a better planning process and management operations of the humanitarian agencies. Therefore, this study aims to establish a comprehensive model that characterizes the integrated humanitarian operations management in response to floods natural disasters. The proposed model comprises of two stage approach accounted for all related emergency logistics operations in preparedness and response phases of disaster cycle management. The first stage concerns the preparedness and initial response decisions while the second stage has been developed as decision support tool for underlying the problem in flood disaster response phase.

Humanitarian Operations Management

In this study, the two major phases of emergency management, which consist of the preparedness and response stages in pre-and post-disaster operations, respectively, are considered in regard to flooding disasters.

The preparedness stage consists of a planning system that is emplaced before a disaster occurs in order to decide on the locations of related facilities and relief supplies. The schemes that are usually taken into consideration during this stage include the selection of distribution centers (DCs) and stock prepositioning levels. The response stage is the latter process and includes the evacuation planning executed right after the disaster happens, followed by distribution of relief supplies. The initial transportation plan must be efficiently determined in order to support the rapid movements required to deliver relief supplies from selected DCs to demand destinations, both in evacuation centers (ECs) and to those still in the affected areas. Finally, unlike other natural disasters, a massive flood often requires decision-making on temporary depot locations that will need the ability to move over time. Hence, the need for transportation and temporary depot location planning updates must be taken into the consideration in the overall relief supply model as well. This will be discussed in greater detail below.

First, facility and stock location models are popular for use in solving problems that focus on the preparedness stage, whereas distribution models are primarily applied to problems that focus on the post-disaster phase in the immediate aftermath of a disaster. These characteristics are affected by activities that must be performed at each point in a disaster lifecycle system. Figure 1 shows the humanitarian operations management timeline used in this study. The most important factor in disaster preparedness is determining 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 standing levels of inventory could impose uncomfortable cost burdens on humanitarian organizations because of their limited funds and operating resources. Thus, designing effective supply chain and logistics systems for humanitarian organizations is a matter of great importance.

Once disaster strikes, relevant government or aid agencies send logisticians to the affected areas in order to assess the type and amount of relief supplies needed. In our case study of flooding, floodwater severity in the city could be determined by monitoring gauges and factoring in the seven-hour period. Based on this information, aid agencies then begin to implement the evacuation plan during the initial phase of the response operations. More specifically, the evacuation must be achieved within seven hours from the detection of imminent flooding. In this step, the process of selecting ECs includes setting priorities for evacuating particular communities, as well as reviewing specific disaster scenarios that incorporate estimated transportation requirements and relief demands.

However, in reality, not everyone will be able (or willing) to travel to an EC, so there will always be a number of people that remain at their residences in the flooded area. In response to this characteristic problem, relief supplies must be distributed to demand destinations both in ECs and within the affected area itself. This means that connecting supply distribution to the evacuation planning process is crucial in this stage because the system requires the rapid distribution of aid supplies in order to satisfy the demands of all affected people in the entire chain. In particular, the initial vehicle transportation plan must be determined by following not only the demand at ECs, but also considering the people who will remain behind in the affected area.

Typically, as in the flood disaster test case examined in this study, flooding tends to last longer than other natural disasters. In other words, it may be necessary to continue the response phase for several days, or even months. As stated above, there are two types of demand destinations in this specific relief chain: ECs and residents in the affected areas, so the need for facilities known as temporary depots is vital in this stage.

In this case study, boats are needed to deliver supplies for the remaining demand in flooded areas because trucks or other forms of land transportation will be no longer applicable due to water obstacles, as shown in Figure 1. One of challenges at this stage is the dynamic process of the problem referred to as the changeable impact of floods. As part of the main trust of an ideal emergency response operation, a framework for the specific problem of temporary depot locations must be considered, along with the rapid deployment of resources and aid within the first 72 hours.

The temporary depot location problem involves optimizing resource allocation among affected people in flood disaster situations by minimizing the cost of logistics operations while maximizing the assistance provided to the people affected. More specifically, the temporary depots location problem determines (1) location of temporary depots, (2) delivery schedules, (3) vehicle routes, and (4) the amount of emergency supplies to be delivered to demand locations during disaster relief operations.

The differences between temporary depot and commercial logistic location problems center on the fact that temporary depots are not storage facilities. Instead, their purpose is to provide points for transferring relief supplies from one carrier type to another, in this case trucks to boats, ideally at the flood boundary itself. Furthermore, unlike other natural disasters that focus on DCs, massive floods often require updating decisions on temporary depot locations over time. Therefore, the need for an effective temporary depot location plan is the last crucial decision in this problem description.

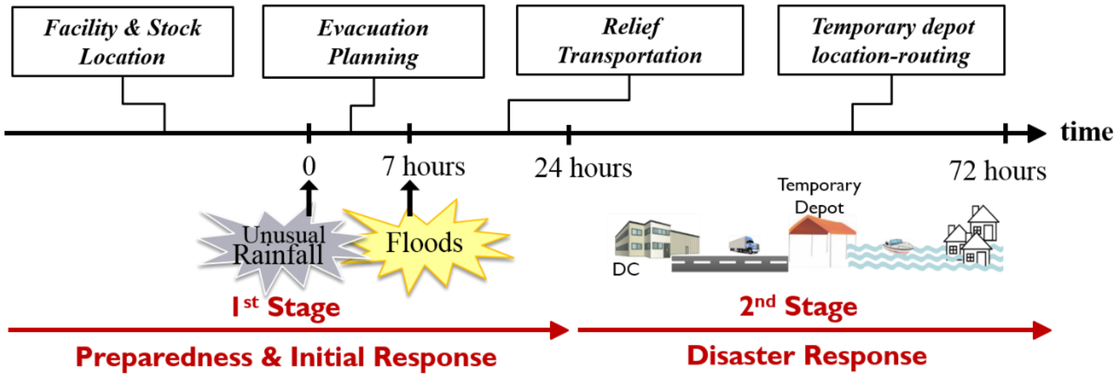

Figure 1 - Humanitarian operations management timeline used in this study

First stage model for the integrated preparedness and initial response

The mathematical formulations in this section are used for the first stage of the integrated preparedness and initial response model. We refer readers to our former work (Manopiniwes and Irohara, 2017) for information on this stage of problem. The model for disaster preparedness decision-making takes the expected outcomes of the response stage into consideration. The decisions that are made before a disaster strikes are usually made with consideration for all possible scenarios, while decisions that are made afterward must focus on a specific scenario. To allow for this uncertainty, the model calculates the expected costs for each of several scenarios. Stochastic programming allows for several different-decision making processes to be integrated, as will be described below.

Pre-disaster Decisions:

- The selection of the local relief DC locations. These are to be used for receiving the relief supplies from the state level and dispatching them to the demand points
- The amount of relief supplies to be stored at each DC

Scenario-specific Post-disaster Decisions:

- The distribution assignments for each DC specifying which demand destinations are to receive relief supplies. These include ECs as well as residents that have not been evacuated
- Evacuation operations for moving all stranded residents in affected communities to their assigned ECs
- The initial transportation plan for vehicles (with their relief supply loading amounts) for each scenario

Since cost minimization is the most common perspective that appears in logistics and supply chain problems, the first objective function is to minimize the total network cost calculated as related to the relief chain for preparedness and response in the pre- and post-disaster stages, respectively. The index sets employed in the formulation of the first stage preparedness are the sets of DCs (I). The binary decision variable x_i is 1, if warehouse i is selected to be operating, 0 otherwise, for each DC $i \in I$. In addition, the decision variable m_i represents the inventory level of relief supply in DC i for all $i \in I$. The parameters of the first stage preparedness formulation are the DC establishment costs f_i and the holding cost g_i, for $i \in I$. The scenarios are denoted $\omega \in \Omega$ in the formulation. The first objective function of the stochastic programming model is given as

$$\text{minimize} \quad \sum_{i \in DC} f_i x_i + \sum_{i \in DC} g_i m_i + E_{\Omega}[Q(x_i, m_i, \omega)]$$

The first objective function of this stage incorporates the total cost of establishment DCs in order to provide an incentive to execute the disaster preparedness at the lowest cost possible, as well as the expected value of the initial response stage solution with respect to disaster scenarios, $E_{\Omega}[Q(x_i, m_i, \omega)$. The initial response stage considers operational movements right after the disaster occurs, which are the evacuation cost and transportation cost of relief supplies specified for each different scenario. $Q(x_i, m_i, \omega)$ is the summation of 1) the total evacuation cost from the affected community to the EC, 2) the total transportation cost to deliver relief supplies from DCs to community, and 3) the total transportation cost to deliver relief supplies from DCs to ECs.

However, the model should not be solely cost based, it must also provide equity-based solutions that consider the optimization of multiple objectives because it deals primarily with the pain and suffering of people in emergency situations. Thus, equity and fairness must be at the forefront of model considerations, even though they are considerations that are commonly ignored in many commercial logistics and supply chain problems. Although there are several ways of formulating the problem of how to maximize equity (e.g., as a *p*-center problem, or a minimization problem for the distance or response time), we consider another decision variable $\delta_{\max}(\omega)$, defined as the maximum response time for each demand point in each scenario ω. Here, the introduction of the second objective function using a *p*-center approach is presented to minimize the expected maximum response time between facilities and demand points both in communities and ECs.

$$\text{minimize} \quad \sum_{\omega\in\Omega} prob(\omega)\delta_{\max}(\omega)$$

Multi-objective stochastic programming is then formulated to obtain tradeoffs between cost and equity aspects. A weighted sum method normalization technique is then applied to solve the proposed model in order to produce trade-offs between cost and equity by imposing an efficient frontier via the construction of multi-criteria decision-making. The stage problem allows decision-makers to evaluate the necessary planning budget, as well as the required facilities, in order to minimize the acceptant inequity among disaster victims.

Second stage disaster response with temporary depot location problem

To formulate the problem for the second stage disaster response, the use of a multi-period approach needed to describe the location-routing problem is presented. In addition, considering multimodal transportation is considered in order to more closely mimic the actual behavior of a disaster. The mixed-integer programming model proposed in this section is adapted from the work of Afshar and Haghani (2012) that focuses on the response stage of a disaster management system

Illustrative examples are presented in order to demonstrate how the proposed models can be used to optimize the temporary depot locations for each time period. Since it is certainly agreed that the first three days (72 hours) are critically important for the response stage of an emergency management system, the example results in this study refer to the solutions obtained based on information that begins immediately after the city has been stricken by floodwaters as the “first 72-hour delivery plan”.

Time scale considerations are important because they have significant affects on network performance. For example, problem sizes may increase significantly with shorter time steps due to the number of time scales in the planning horizon, while longer time steps work to keep problems at reasonable sizes. In this study, hours are more appropriate than minutes when it comes to describing those activities needed in the flooding response stage. Both delivery flow and transfer nodes requires at least a couple hours, but less than six hours, to complete. Thus, six-hour periods are considered appropriate for treating this problem.

The illustrative results are displayed following the assumption of dynamic demand. Here, we assume that floodwaters cause a certain amount of Scenario 1 demand at the beginning that amounts to 12,971 demands in total, and that the floodwaters become massive during the next day, as shown in Scenario 2, resulting in a total of 48,041 demands, as shown in Figure 2.

First day: Scenario 1

Second day: Scenario 2

Figure 2 - Optimal location solutions

Figures 3 and 4 show the results of temporary depot location selection between the beginning of flood at t=1 and the next 24 hours at t=5, during which the flood becomes massive for the unlimited capacity case. In the beginning, the 13 known demand points identified based on Scenario 1 projected floodwaters are served by two temporary depots are optimally located at the flood boundary area, where they receive relief supplies from the DCs transported by trucks and then provide deliveries to the demand points in affected area using boats.

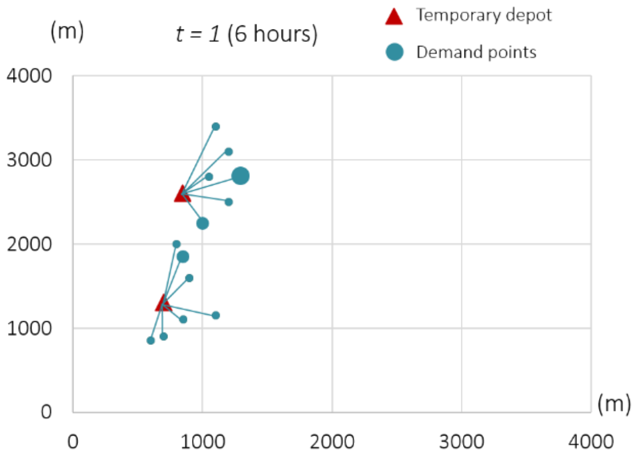

Figure 3 - Optimal solutions for first time period temporary depot location selection

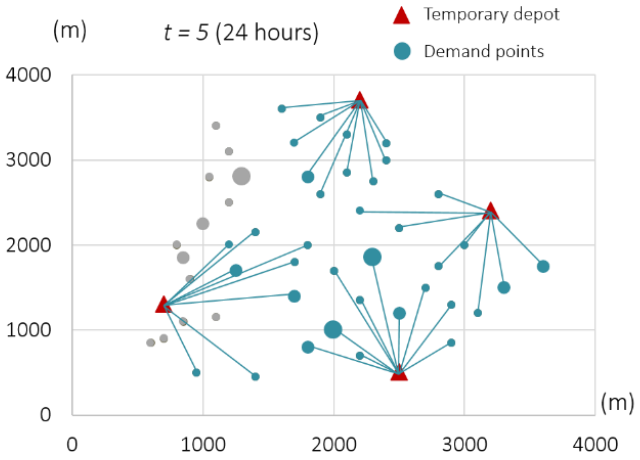

Figure 4 - Optimal solutions for fifth time period temporary location selection

Over the course of the next day at t=5, total demand points increase significantly due to the floods described in Scenario 2. Since the former 13 demand points (grey color) were completely satisfied within t=5, one of the two early stage depots is moved to a new location in order to serve those added demands, while the other remains at the same location in order to serve newly encountered close-by demand points. Two additional temporary depots are established to provide deliveries to remaining demand.

Discussions and Conclusions

We formulated stochastic programming for the first stage model, which takes into the consideration the most important three components: facility and stock location, evacuation planning, and relief transportation. The decisions that are made before a disaster hits, such as facility and stock location problems, are usually made while taking into consideration all possible scenarios. The decisions that are made afterward must depend on the actual scenario. These include evacuation planning and relief transportation in the initial response stage of the problem. To develop a framework for effective relief operations, the model considers not only a cost-based, but also an equity-based solution approach to the multiple objectives optimization problem. Solving this problem stage provided empirical insights about how change is brought about during disaster operations. It also suggested ways to compromise between cost considerations and relief victim equity.

The second stage extended the contribution by focusing on the operational level in response to immediate aftermath of a flood disaster. The location-routing model was proposed in response to the temporary depot problem that is particular to such disasters. To formulate this problem, the use of a multi-period approach to describe the problem was presented, and multimodal transportation was considered in order to more closely mimic the realistic behavior of a flooding disaster. A unique and special characteristic of floods relates to their dynamic capabilities. While floods may not strike as urgently as earthquakes or other natural disasters, they are unstable in size and have potential impacts over long periods of time. In particular, the most common transport channels during floods are trucks in unaffected areas and boats in affected areas.

Our proposed model controls the flow of all relief commodities, from the sources all the way through the chain until they are delivered to the hands of the recipients. This model provided the foundation for an integrated operation plan that proved capable of minimizing delays and distributing the limited resources in a way that optimally satisfied the overall system.

Finally, since there are a number of possible extensions for this model, future research will explore larger and more complex problems. A further major finding regarding the uncertain parameters in the first stage is the increase in solution time entailed by the occurrence of a larger number of realizations. The use of algorithms is expected provide significant opportunities for improvement when problem sizes and complexity increase, and this can be expected to facilitate finding proper and satisfactory solutions to problem processes.

References

Afshar, A. and Haghani, A. (2012), “Modeling integrated supply chain logistics in real-time largescale disaster relief operations”, *Socio-Economic Planning Sciences*, Vol. 46, pp. 327-338.

Banomyong, R., Varadejsatitwong, P. and Oloruntoba, R. (2017), “A systematic review of humanitarian operations, humanitarian logistics and humanitarian supply chain performance literature 2005 to 2016”, *Annals of Operations Research*, pp.1-16.

Jabbour, C.J.C., Sobreiro, V.A., de Sousa Jabbour, A.B.L., de Souza Campos, L.M., Mariano, E.B. and Renwick, D.W.S. (2017), “An analysis of the literature on humanitarian logistics and supply chain management: paving the way for future studies”, *Annals of Operations Research*, pp.1-19.

Manopiniwes, W., & Irohara, T. (2017), “Stochastic optimisation model for integrated decisions on relief supply chains: preparedness for disaster response”, *International Journal of Production Research*, Vol. 55(4), pp. 979-996.