Optimization and Simulation Modeling of Disaster Relief Supply Chain: A Literature Review

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Abstract:

Recent natural and man-made disasters underscore the need of a resilient and agile disaster relief supply chain to mitigate the damages and save people's lives. Optimization and simulation modeling have become powerful and useful tools to help decision makers tackle problems related to disaster relief supply chain. This paper reviews optimization and simulation models used in the field of disaster relief supply chain. We review the literature of the facility location optimization problems of disaster relief supply chain under different types of disastrous events. We review the literature of simulation models on supply chain design and disaster relief distribution operations. Finally, we propose two future research directions for disaster relief supply chain modeling.

Keywords:

Disaster Relief Supply Chain, Optimization, Simulation, Modeling

1. Introduction

Recent natural and man-made disasters such as Hurricane Katrina in 2005, Hurricane Rita in 2005, Hurricane Gustav in 2008, flooding in North Dakota in 2009, earthquake in Haiti in 2010, and nuclear disaster caused by massive earthquake and tsunami in Japan in 2011 underscore the need of a resilient and agile disaster relief supply chain to mitigate the damages and save people's lives. An ineffective disaster relief supply chain may cause death, sickness, epidemics, and social turmoil. For instant, Hurricane Katrina in 2005 makes 1,300 death tolls and $200 billion of damages. According to some researchers' studies [*1*], more than half of the planet's 20 costliest catastrophes have occurred since 1970 and natural disasters are increasing in frequency and intensity in the last ten years due to several reasons such as quickly growing population, larger concentration in high-risk areas, and increasing social and economic interdependency. Figure 1 (a) shows the worldwide trend of the number of natural disasters and man-made disasters; Figure 1 (b) indicates the trend of the number of declared disasters by FEMA in the U.S. The data in Figure 1 illustrates why the demand for disaster relief supply chain is increasing and indicates that developing a better disaster relief supply chain is essential and immediately needed.

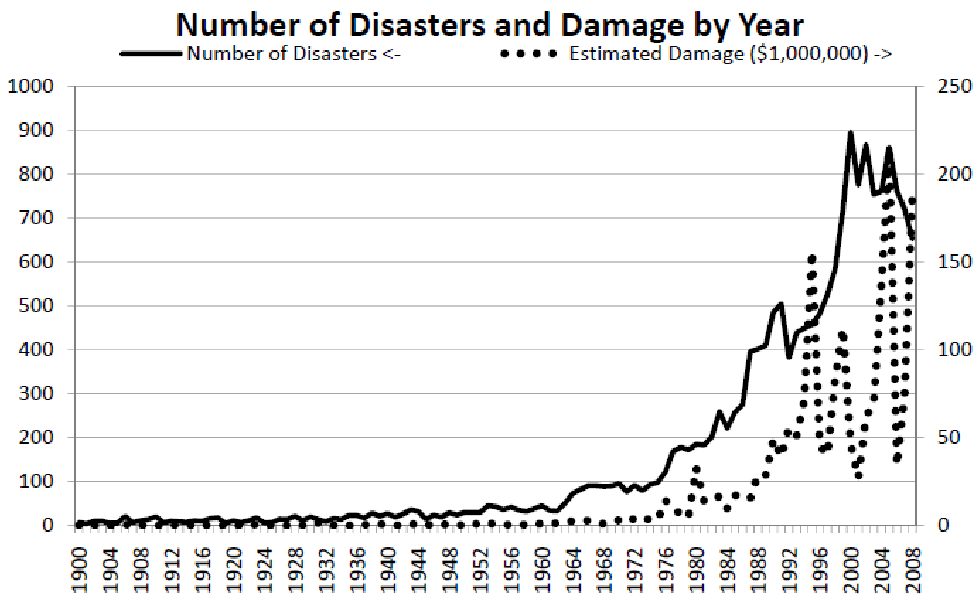

Figure 1 (a) International Disasters Trend.
(Source: http://www.emdat.be/database)

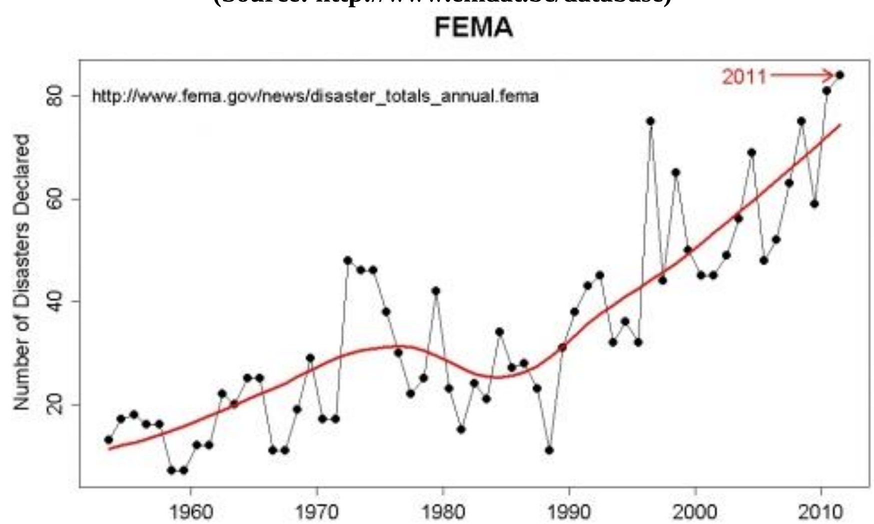

Figure 1(b) U.S. Disasters Trend

A disaster relief supply chain starts from suppliers of federal and local government or private donors to regional distribution warehouses, to local warehouses, finally to the disaster recovery centers (DRC) as illustrated in Figure 2. The disaster relief supply chain is different from traditional commercial supply chains from different aspects such as a huge surge of sudden demand, damaged transportation network, demand uncertainty of victims, crippled communication infrastructure, short lead times, and many other uncertainties. Nevertheless, there are lessons that can be borrowed from the well-studied commercial supply chains and vice versa.

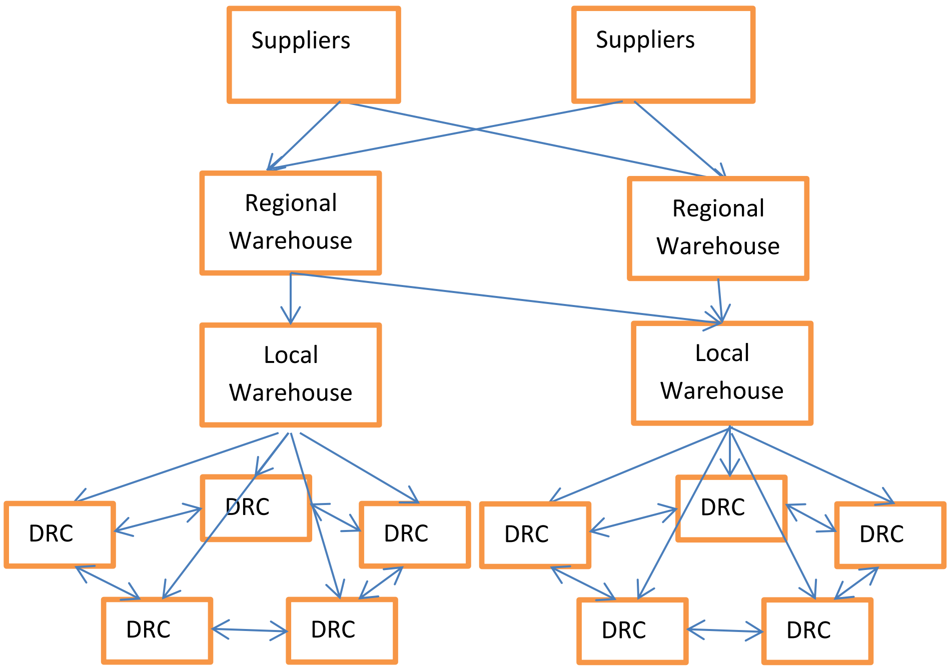

Figure 2 Disaster Relief Supply Chain

Several academic research studies were conducted to investigate different aspects of disaster relief supply chain management. Lodree Jr. and Taskin [*2*] proposed an insurance risk management framework for decision makers to quantify the risks and benefits associate with stocking decision for disaster relief efforts or supply chain disruption. Maon et al [*3*] developed a theoretical model for developing supply chain in disaster relief operations through cross-sector socially oriented collaboration. Falasca et al [*4*] developed a decision support framework for assessing supply chain resilience to disasters. In addition, there are some articles focusing on humanitarian supply chains [*5*,*6*,*7*,*8*,*9*]. Disaster relief supply chains can be treated as a subset of humanitarian supply chains. However, most of the aforementioned researches study the disaster relief supply chain in a qualitative manner. To better understand how to apply the quantitative modeling methodologies to the disaster relief supply chain, we will conduct literature review on the disaster relief supply chain modeling in this paper.

Based on the review of existing studies, we have identified the two focus areas related to disaster relief supply chain modeling: 1) Optimal facility location modeling for disaster relief supply chain; and 2) Simulation modeling for the disaster relief supply chain. The following sections provide an expanded literature review on the two focus areas.

2. Facility Location Optimization Modeling for Disaster Relief Supply Chain

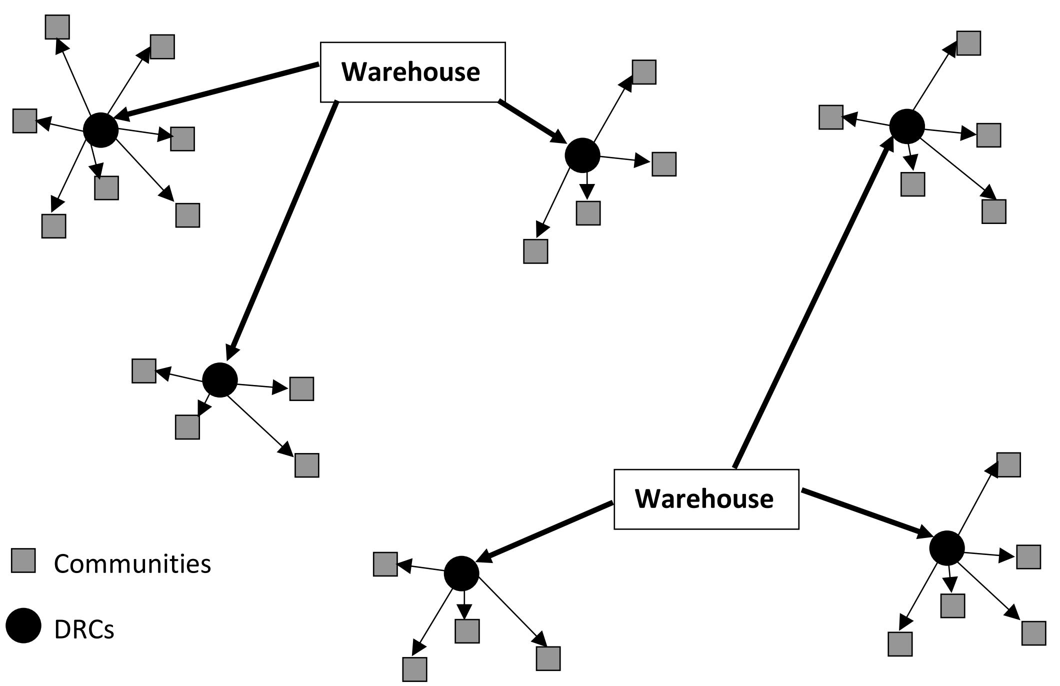

Figure 3 Distribution Network for Disaster Relief Supply Chain

When natural disasters occur, an efficient disaster relief supply chain plays a critical role in quickly distributing relief supplies to the affected area for rapid recovery. In the distribution network shown in Figure 3, warehouses distribute relief supplies to Disaster

Recovery Centers (DRC); DRCs supply the relief supplies for the affected Communities; and Communities can also obtain relief supplies directly from warehouses. A DRC is a readily accessible facility or mobile office where disaster victims can obtain relief goods and assistance. Warehouses are usually built with extreme care and their failure probabilities during disastrous events are negligible. However, DRCs are subject to disruptions caused by disastrous events and fail with various probabilities. This is because secondary disasters such as tsunami, flood, and nuclear accidents may happen after the original disasters such as earthquakes, hurricanes, and tornados. Thus, the disruptions of disaster relief distribution facilities should be taken into account. To better serve the disaster victims and minimize the corresponding operational and logistic costs, it is important to seek the optimal locations of the DRCs and warehouses.

Facility location problems have been extensively studied for decades. A good reference of facility location modeling can be founded in Daskin (1995)'s book [10]. However, the traditional deterministic facility location models, such as set-covering models, p-center models, p-median models, and fixed charge facility location problems, are not applicable for this problem because it involves a significant amount of demand uncertainties and supply disruptions. Snyder [11] conducted a comprehensive review on facility location under uncertainty, mainly focusing on stochastic and robust facility location models. Recently, a number of researchers, such as Wagner et al. [12]; Murali et al. [13]; Caro et al. [14], studied various problems related to facility location under demand uncertainty in business settings. In this paper, we mainly focus on the facility location studies on demand uncertainty caused by disastrous events.

Dekle et al. [15] developed a set-covering model and a two-stage approach to identify the optimal DRC sites. Their main objective was to minimize the total number of DRCs, subject to each county's residents being within certain distance of the nearest DRC. They found that their model provided significant improvements to the original FEMA location criteria, while maintaining acceptable travel distances to the nearest DRC. Horner and Downs [16] conducted a similar study to optimize DRCs locations given the positions of disaster relief supply warehouses. Given the number and locations of initial warehouses, the authors formulated the problem as a multi-objective integer programming model. The first objective was to minimize the transportation costs of servicing DRCs from warehouse locations; and the second one was to minimize transportation costs between DRCs and neighborhoods in need of relief goods.

Snyder and Daskin [17] developed a reliable facility location model for choosing facility locations to minimize cost while also taking into account the expected transportation cost after failures of facilities. The objective of their paper is to choose facility locations that are both inexpensive under traditional objective functions and also reliable. The reliability approach is new in the facility location literature. They formulated the reliability models based on both the p-median and the incapacitated fixed-charge location problem. The developed model is solved by a Lagrangian relaxation algorithm. Berman et al. [18] also developed a reliable facility location model based on the p-median problem. In their research, each facility is assigned a failure probability. The objective is to minimize the expected weighted transportation cost and the expected penalty for certain customers not being served. They found the optimal location patterns are seen to be strongly dependent on the probability of facility failure, with facilities becoming more centralized, or even colocated, as the failure probability grows. The developed model has a nonlinear objective function and is difficult to solve by exact algorithms. These authors thus proposed several exact and heuristic solutions approached for this problem.

Hassin et al. [19] investigate a facility location problem considering the failures of network edges. Their goal is to maximize the expected demand that can be served after disastrous events. In their study, it is assumed that a demand node can be served by a facility if it is within a certain distance of the entity in the network that survived disaster. The failures of network edges are assumed to be dependent on each other. These authors formulate the problem as an exact dynamic programming model and develop an exact greedy algorithm to solve it. Eiselt et al. [20] also propose a reliable model for optimally locating p facilities in a network that takes into account the potential failures of road network links and nodes. These authors develop a low-order polynomial algorithm to solve the proposed facility location model.

Li and Ouyang [21] examined a continuous reliable uncapacitated fixed charge location (RUFL) problem where facilities are subject to spatially correlated disruptions that occur with location-dependent probabilities (due to reasons such as natural or man-made disasters). A continuum approximation approach is adopted to solve the developed model. The authors consider two methods to model the spatial correlation of disruptions, including positively correlated Beta-Binomial facility failure. Cui et al. [22] also study the RUFL problem and proposed a compact mixed integer program (MIP) formulation and a continuum approximation model to minimize initial setup costs and expected transportation costs in normal and failure scenarios. Similar to Snyder and Daskin [17], Cui et al. [22] assigned each customer to multiple levels to ensure the robustness of the final facility location design. They also develop a custom-designed Lagrangian relaxation algorithm to solve the proposed MIP model. Murali et al. [23] considered a capacitated facility location problem to maximize relief coverage, taking into account a distance-dependent coverage function and demand uncertainty. They formulated this problem as a maximal covering location problem and developed a locate-allocate heuristic to solve the problem.

Some researchers focused on the efficiency and robustness design of disaster relief supply chain. Shukla et al. [24] proposed a design framework that addresses the facility and link failure explicitly by accounting for their impact on network's performance measures of efficiency and robustness. They used a scenario planning approach and formulated a mixed integer linear program model with the objective of maximizing both efficiency and robustness. It also evaluated the trade-offs between efficiency and robustness. Hong et al. [25] proposed and compared two robust models, Robust Integer Facility Location (FIFL) and Robust Continuous Facility Location (RCFL) models, for the same supply chain network settings as Shukla et al. [24] studied. They found that the total logistic cost and robustness level of the RCFL outperforms those of other models while the performance of RFL and RIFL is mixed between the cost and robustness index.

In this section, we mainly reviewed the articles that directly related to the facility location problem under demand uncertainty caused by disastrous events. The literature review in this section may not be exhaustive, but it presents readers a snapshot about the facility location modeling for disaster relief supply chain.

3. Simulation Modeling of Disaster Relief Supply Chain

According to Green and Kolesar [*26*], a simulation model for disaster relief is the foundation on which new policies and tactics can be developed and evaluated. In order to develop decision-making tools for disaster relief supply chain, simulation can be an excellent tool for understanding the impact of disasters, disaster relief operations, and the consequences of alternative policies. Simulation models also serve as a test bed as real-life experimentation of analytical tools with actual disaster situations would be too difficult and risky.

Various simulation models have been developed for disaster relief supply chain in response to different types of disasters. Several researchers used simulation models to design and evaluate disaster relief supply chains. Bravata et al. [*27*] develop simulation models to study strategies for stockpiling and dispensing for anthrax bioterrorism and modeled regional and local supply chain for antibiotics and medicinal supplies to estimate mortality. They concluded that the critical determination of mortality following anthrax bioterrorism is the local dispensing capacity (throughput rate). Wein and Liu [*28*] developed a supply chain model of milk to analyze the impact of a bioterrorism attack of botulinum toxin, which has a potential death rate of 50% with a chance of 400,000 people contaminated. They recommended investment in prevention through enhanced security, in the heat pasteurization process and in-process testing for toxins. Lee et al [*29*] developed a simulation modeling framework to simulate the disaster relief supply chain and distribution operations especially for hurricane disaster. The model can evaluate a wide range of disaster scenarios, assess existing disaster response plans and policies, and identify better approaches for government agencies and first responders to prepare for and respond to disasters.

For distribution operations of disaster relief goods, Hupert et al. [30] used discrete event simulation models to determine staffing levels for entry screening, triage, medical evaluation, and drug dispensing stations in a hypothetical antibiotic distribution center operating in low medium, and high disease prevalence bioterrorism response scenarios. They concluded that simulation modeling is an useful tool in developing the public health infrastructure for bioterrorism response. Aaby et al. [31] developed discrete-event simulation models and capacity-planning and queueing-system models to improve clinical distribution of medications and vaccines in event of outbreak of contagious diseases. They validated these models using data that they collected during full-scale simulations of disease outbreak. Whitworth [32] used discrete-event simulation to help one community develop its plan for responding to an anthrax attack. The model determined how many DRCs the community would need, how to staff them, and how to manage client traffic and parking. Lee et al. [33] described RealOpt, a simulation and decision-support system for planning large-scale emergency dispensing clinics to respond to biological threats and infectious-disease outbreaks. The system allows public-health administrators to investigate clinic-design and staffing scenarios quickly. Lee [*34*] developed a simulation model that includes shipment of emergency medical supplies to DRCs from a city-owned warehouse in addition to DRC operational model. He reported that cross shipping of vaccines or antibiotics among DRCs can improve the coverage when the overall supply is limited or when there is an imbalance between supply and demand at DRCs. These models only focus on the DRC operations without modeling the relief goods distribution for the whole disaster relief supply chain.

4. Summary and future research

The paper reviews optimization and simulation models used in the field of disaster relief supply chain. For the optimization models, we primarily focus on the literature of the facility location of disaster relief distribution warehouses and disaster relief centers under different types of disastrous events. For the simulation models, we mainly concentrate on the literature of simulation models on supply chain design and disaster relief distribution operations. Based on the review, we identify two possible future research directions for the field of disaster relief supply chain. First, a comprehensive joint model of optimization and simulation model for the disaster relief supply chain is absent. This calls for development a comprehensive model to optimize and simulate the disaster relief supply chain. Second, most cited researches focused on the disaster relief in urban areas and rural areas were historically overlooked. A comprehensive model is needed for rural communities to better prepare for potential natural or man-made disasters and to improve their disaster resilience.

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