Omega 52 (2015) 168–179

Contents lists available at ScienceDirect

Omega

journal homepage: www.elsevier.com/locate/omega

Risk based facility location by using fault tree analysis in disaster management ☆

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ARTICLE INFO

Article history:
Received 19 August 2013
Accepted 20 April 2014
Processed by Salazar-Gonzalez
Available online 14 May 2014

Keywords:
Location
Risk
Fault tree analysis
Vulnerability
Disaster management
p-Center risk model

ABSTRACT

Determining the locations of facilities for prepositioning supplies to be used during a disaster is a strategic decision that directly affects the success of disaster response operations. Locating such facilities close to the disaster-prone areas is of utmost importance to minimize response time. However, this is also risky because the facility may be disrupted and hence may not support the demand point(s). In this study, we develop an optimization model that minimizes the risk that a demand point may be exposed to because it is not supported by the located facilities. The purpose is to choose the locations such that a reliable facility network to support the demand points is constructed. The risk for a demand point is calculated as the multiplication of the (probability of the) threat (e.g., earthquake), the vulnerability of the demand point (the probability that it is not supported by the facilities), and consequence (value or possible loss at the demand point due to threat). The vulnerability of a demand point is computed by using fault tree analysis and incorporated into the optimization model innovatively. To our knowledge, this paper is the first to use such an approach. The resulting non-linear integer program is linearized and solved as a linear integer program. The locations produced by the proposed model are compared to those produced by the p-center model with respect to risk value, coverage distance, and covered population by using several test problems. The model is also applied in a real problem. The results indicate that taking the risk into account explicitly may create significant differences in the risk levels.

1. Introduction

Schulz [1] defines a *disaster* as "an occurrence of widespread severe damage, injury or loss of life or property with which a community cannot cope and during which the society undergoes severe disruption" and *Disaster Management* (DM) as "the range of activities designed to maintain control over disaster and emergency situations and to provide a framework for helping at-risk persons to avoid or recover from the impact of the disaster. DM deals with situations before, during and after a disaster". The activities in the context of DM are generally considered in four phases: *mitigation*, *preparedness*, *response*, and *recovery* (e.g., [2-4]). Coppola [4] defines these phases as follows: "*Mitigation* involves reducing or eliminating the likelihood or the consequences of a hazard or both. Mitigation seeks to treat the hazard such that it impacts society to a lesser degree. *Preparadness* involves equipping people who may be impacted by a disaster or who may be able to help those impacted with the tools to increase their chance of survival and to minimize their financial and other losses. *Response* involves taking action to reduce or eliminate the impact of disasters that have occurred or currently occurring, in order to prevent further suffering, financial loss, or a combination of both. *Relief*, a term commonly used in international disaster management, is one component of response. *Recovery* involves returning victims' lives back to a normal state following the impact of disaster consequences. The recovery phase generally begins after the immediate response had ended and can persist for months or years thereafter". The activities related to mitigation and preparedness, i.e., pre-disaster phase, are considered as *Risk Management* while the activities related to response and recovery, post-disaster phase, are considered as *Crisis Management* (e.g., [5])

Coppola [4] points out that response and recovery alone are not effective means of managing disasters if they are performed in the absence of a comprehensive regimen of preparadness and mitigation activities. Coppola [4] also points out that there is a shift towards *risk reduction-based disaster management*. This is also

☆ This manuscript was processed by Associate Editor Salazar-Gonzalez.

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http://dx.doi.org/10.1016/j.omega.2014.04.003
0305-0483/

emphasized in the framework developed at the World Confence on Disaster Reduction held in Japan in 2005 [6]. Three strategic goals outlined in that framework are as follows:

1. The more effective integration of disaster risk considerations into sustainable development policies, planning and programming at all levels, with a special emphasis on disaster prevention, mitigation, preparedness, and vulnerability reduction,
2. The development and strengthening of institutions, mechanisms and capacities at all levels, in particular at the community level, that can systematically contribute to building resilience to hazards,
3. The systematic incorporation of risk reduction approaches into the design and implementation of emergency preparedness, response, and recovery programmes in the reconstruction of affected communities.

In this context, this paper studies one of the problems in the pre-disaster phase from a risk management perspective. Specifically, the study investigates the problem of locating the facilities that are used for pre-positioning stocks needed in the first stages of a disaster relief operation. The paper explicitly considers the risk that a demand point (probable disaster point) may not get service from the located facilities and tries to choose the locations of the facilities to minimize the maximum risk.

Balcik and Beamon [7] describe the general flow of resources to the disaster-affected areas as shown in Fig. 1. The resource requirements in the assessment phase are minimal while the resource requirements in the deployment phase increase dramatically. The need for resources stabilizes in the sustainment phase and decreases in the reconfiguration phase. The length and importance of each phase varies depending on the characteristics of the disaster and the characteristics of the affected areas. However, Balcik and Beamon [7] state that "the speed of relief operations during the first days of the disaster significantly affects the lives of many people, threatened by the disaster. The ability of a relief organization to mobilize its resources during assessment and deployment phases is critical to the success of disaster response".

One strategy that has gained importance and adopted by the relief organizations to enhance their emergency response capacity and hence to respond to a disaster effectively is to *pre-position supplies*. This strategy is important because, as Balcik and Beamon [7] state, most of the critical supplies arriving at the disaster areas are sourced from relief organizations' pre-positioned stocks. Similarly, Jahre and Heigh [8] state that the performance of a disaster relief operation is much dependent on the level of preparedness.

Thomas and Mizushima [9] define *pre-positioning* as "the storage of inventory at or near the location at which it will be used". Although the importance of locating resources close to the disaster area for faster delivery of supplies to the affected people cannot be overemphasized, this also poses an important risk; the facilities (and hence supplies) themselves may be damaged or inaccessible due to the disaster(s). This study takes this fact into account in determining the locations of facilities. This is achieved implicitly as a part of the *vulnerability of a demand point* that depends on the locations of facilities (whether the demand point is covered or not) and computed by using *Fault Tree Analysis* (FTA). The structure in the FTA is incorporated into an optimization model. The resulting model is a non-linear mixed-integer programming model that aims to minimize the maximum risk that a demand point may be exposed to. The non-linear model is linearized and solved as a linear integer program.

The rest of the paper is organized as follows. Section 2 reviews the literature. Section 3 gives the risk definition used in the paper and Section 4 explains the fault tree analysis and how to compute the vulnerability of a demand point. Section 5 and Section 6 give the p-center risk and p-center models, respectively. Section 7 explains how the models are solved. Section 8 analyzes the model by considering several factors. Section 9 defines an application of the proposed model. Section 10 concludes the paper.

2. Literature review

DM has mostly been related to the social research and hence there is a rich literature in this context. The survey papers by Altay and Green [3] and Galindo and Batta [10] indicate that DM has gained importance in the last two decades in OR/MS (Operations Research/Management Science) research as well. Altay and Green [3] review 109 papers from 1980 to 2005 while Galindo and Batta [10] review 156 papers from 2006 to 2010. They classify the papers with respect to several criteria and identify potential research directions for the OR/MS community. In this paper, we consider only the optimization models with a focus on *facility location* in DM and on *reliable facility location* in general.

Caunhye et al. [11] review optimization models in emergency logistics. They categorize the studies into two main categories: (1) facility location and (2) relief distribution and casualty transportation. They state that most facility location models combine

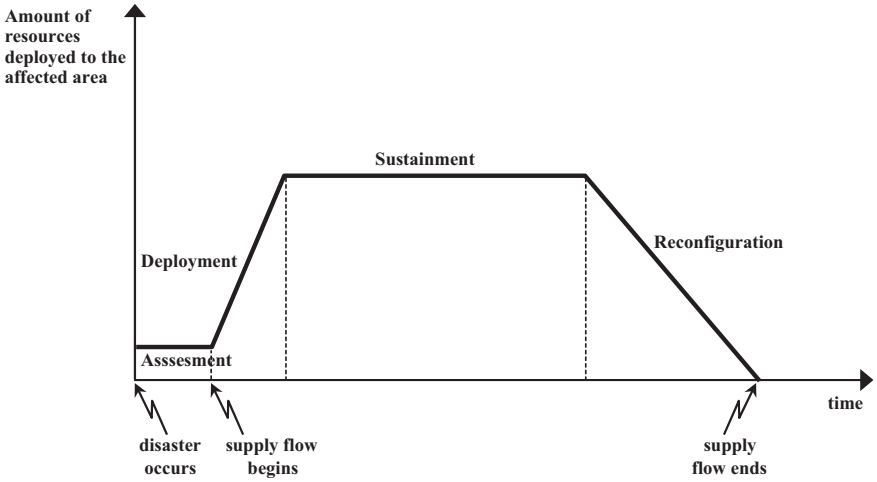

Fig. 1. Relief mission life cycle (Balcik and Beamon [7]).