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Pre-positioning disaster response facilities at safe locations: An evaluation of deterministic and stochastic modeling approaches

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ABSTRACT

Choosing the locations of disaster response facilities for the storage of emergency supplies is critical to the quality of service provided post-occurrence of a large scale emergency like an earthquake. In this paper, we provide two location models that explicitly take into consideration the impact a disaster can have on the disaster response facilities and the population centers in surrounding areas. The first model is a deterministic model that incorporates distance-dependent damages to disaster response facilities and population centers. The second model is a stochastic programming model that extends the first by directly considering the damage intensity as a random variable. For this second model we also develop a novel solution method based on Benders Decomposition that is generalizable to other 2-stage stochastic programming problems. We provide a detailed case study using large-scale emergencies caused by an earthquake in California to demonstrate the performance of these new models. We find that the locations suggested by the stochastic model in this paper significantly reduce the expected cost of providing supplies when one considers the damage a disaster causes to the disaster response facilities and areas near it. We 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. Thus, the value of the stochastic model is particularly great in realistic, budget-constrained situations.

1. Introduction

To provide responsive and timely service in the event of natural disasters and terrorist attacks, government agencies are developing large disaster response facilities to pre-position emergency supplies [1]. For example, in the United States, significant research interest has been generated in the location planning of these facilities after the Centers for Disease Control and Prevention (CDC) were entrusted with the task of establishing the Strategic National Stockpile (SNS). According to the CDC web site [32]:

> Strategic National Stockpile (SNS) has large quantities of medicine and medical supplies to protect the American public if there is a public health emergency (terrorist attack, flu outbreak, earthquake) severe enough to cause local supplies to run out. Once Federal and local authorities agree that the SNS is needed, medicines will be delivered to any state in the U.S. within 12 hours.

This paper focuses on the optimal placement of disaster response facilities like the SNS that will be used to pre-position emergency supplies. Emergency supplies can include food, medicine, potable water, also medical equipment, generators, tents etc. In deciding on suitable locations for pre-positioning warehouses, decision makers need to consider disasters that may affect large geographical areas, with the potential to devastate entire cities. Earthquakes are a typical example, but other large-scale disasters where damage to surrounding areas originates from an epicenter are also applicable. This disaster class may include floods, large scale fires, and even non-natural events such as terrorist bomb attacks on certain target structures.

Many models for locating facilities for pre-positioning emergency supplies have assumed that facilities are robust and will be functioning even in the wake of a natural disaster [1,12]. There exist models that consider facilities that might not be always available at their full capacity, for example Jia et al. [17], Paul and Batta [22], and Beraldi et al. [5]. These models assume that a disaster reduces the capacity of a facility by a certain deterministic fraction. Other models that incorporate damage to facilities, such as Rawls and Turnquist [24], Noyan [21] and Bozorgi-Amiri et al. [8], use stochastic formulations, but are scenario-based and model damage exogenously to the model.

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In contrast to this, both models we develop in this paper explicitly address the uncertainty in the magnitude of damages caused by a large-scale emergency event through the introduction of a distance-damage function.

We compare the performance of these two models in an exemplary case study, using earthquakes in California as the disaster of interest. Our case study reveals that stochastic treatment of damages can have significant impact on the quality of the pre-positioning decision. Our study also shows that the cost advantage of the stochastic model over the deterministic model is especially large when (1) only a few facilities can be placed, and when (2) the uncertainty over the potential damage inflicted by the disaster is high. Thus, the value of the stochastic model is particularly great in realistic, budget-constrained situations, and when the disaster outcome is hard to predict.

To motivate why making location decisions for large-scale emergencies where facilities may fail is different from making location decisions for general facilities, we consider a simple stylized example: suppose there are two cities A and B where population is concentrated, and four potential facility sites – one at A, one at B, and two between A and B as shown in the Fig. 1. We will refer to the two cities as the demand points. The distances are as marked on the figure, and the chance of a disaster occurring at any of the two cities is the same. For the purpose of exposition, we assume that A and B are high risk areas where disasters might occur, and that the possibility of a disaster occurring at other locations is small enough to be ignored.

Suppose we want to construct two disaster response facilities. Location models such as the traditional *k*-median model or models developed by Paul and Batta [22] and Beraldi et al. [5] assume that a reduction in capacity of facilities is unrelated to where the disaster occurs, and would therefore prescribe locating the facilities at sites 1 and 4. However, if a devastating earthquake occurs at city A, most likely facility 1 will be damaged because of its proximity to the disaster and may not be able to satisfy all demands. Aid would have to come from facility 4 which is far away. Similarly, if an earthquake occurs near city B, facility 4 would not be functioning, and aid would have to come all the way from facility 1. This intuitively poor placement decision occurs because these traditional location models assume that facility availability is independent of disaster location, whereas in actuality this is not true.

If one were to condition the functioning of the disaster response facilities on the actual disaster, better solutions might be found. Indeed, the model we present in this paper suggests locating the facilities at sites 2 and 3. When a disaster happens at A, 2 and 3 being relatively far away from the disaster site will still be functioning at a slightly reduced capacity and can combine to send aid. When a disaster happens at B, the same holds true. Locating facilities at sites 2 and 3 saves transportation cost and also reduces response times.

In addition, our paper also addresses other important issues such as the stochastic nature of the damage due to the disaster and the effect of a disaster on multiple cities. We address these issues by explicitly modeling the damage a disaster causes to the cities and facilities in its vicinity as a random variable that is correlated to the location of the disaster via a distance-damage function. Moreover, we provide insight into the impact of the variability of damage intensity on the solution quality through a sensitivity analysis on the coefficient of variation of the random variable describing the damage of the disaster. We also demonstrate the impact that the density of the disaster response facility network has on the respective solution qualities of the models.

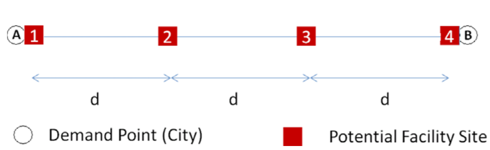

Fig. 1. Illustration to show the shortcomings of naive location models for large-scale emergency cases.

Our modeling approach is based on the intuition that locating a disaster response facility very close to a high risk city or population region may not be optimal as the facility itself might be damaged when needed. This distance-dependence is a reasonable assumption because typically the damage from natural and man-made disasters are highest closest to the primary impact of a disaster such as the epicenter of an earthquake or the track of a hurricane [29].

In this paper, we formulate the distance-dependent large scale emergency pre-positioning model, and we also provide a novel solution algorithm for the stochastic model. This solution algorithm is based on a modification of Benders decomposition, using a greedy heuristic to solve the master problem. To the best of our knowledge, this modification is novel in the literature. Our solution algorithm is formulated for solving the pre-positioning model developed in this paper, but its basic idea should be applicable to a larger class of stochastic location problems. We provide a case study on earthquakes in the state of California to show the performance of our model and to demonstrate the necessity of incorporating the modeling improvements for locating disaster response facilities.

The remainder of this paper is organized as follows. In Section 2, we present an overview of the existing literature. Section 3 provides a new formulation of the pre-positioning problem that considers the effect of a disaster on the facilities and population centers close by, while Section 4 provides effective solution algorithms for solving the model. Section 5 provides a case study of the new models, and Section 6 concludes this paper with a discussion of the contribution of this paper, as well as future research directions.

2. Literature survey

When examining the literature on facility location under uncertainty, two broad categories of problems stand out: (1) problems where the facilities are more or less constantly in use, like warehouses or fire stations, and (2) problems where facilities come into use after some rare event, such as emergency supply warehouses being used after an earthquake.

In that first category, it is reasonable to have models in which the functioning of a facility is independent of externalities like demand. However, the same does not hold true for the second category. Here the functioning of a facility is coupled with the rare event that causes a demand. In the context of this paper, we define “emergency” as a rare, high-consequence, large-scale event, as opposed to “routine” emergencies such as ambulance or police calls.

The literature on facility location under uncertainty is fairly advanced for the first category of problems that were discussed in the preceding paragraph, as can be seen from Berman et al. [6,7] and Snyder and Daskin [30]. Berman et al. [6] discuss the location of facilities whose reliability is dependent on the distance between the facility and the demand point. However, their model was developed for a constant demand class of problems. The chance of providing uninterrupted service goes down as the distance increases. They take into account the uncertainty in roads and transportation links being available and functioning, but they do not take into account the functioning of the facility itself. This is a realistic assumption since these models were designed for a firm providing constant service. However, this assumption makes these models less suitable for emergency facility location. The difference