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Emergency facility location under random network damage: Insights from the Istanbul case

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ABSTRACT

Damage to infrastructure, especially to highways and roads, adversely affects accessibility to disaster areas. Predicting accessibility to demand points from the supply points by a systematic model would lead to more effective emergency facility location decisions. To this effect, we model the spatial impact of the disaster on network links by random failures with dependency such that failure of a link induces failure of nearby links that are structurally more vulnerable. For each demand point, a set of alternative paths is generated from each potential supply point so that the shortest surviving path will be used for relief transportation after the disaster. The objective is to maximize the expected demand coverage within a specified distance over all possible network realizations. To overcome the computational difficulty caused by extremely large number of possible outcomes, we propose a tabu search heuristic that evaluates candidate solutions over a sample of network scenarios. The scenario generation algorithm that represents the proposed distance and vulnerability based failure model is the main contribution of our study. The tabu search algorithm is applied to Istanbul earthquake preparedness case with a detailed analysis comparing solutions found in no link failure, independent link failure, and dependent link failure cases. The results show that incorporating dependent link failures to the model improves the covered demand percentages significantly.

1. Introduction

Uncertainty on the timing, location and magnitude of a natural disaster, as well as how it impacts the disaster area pose serious challenges for disaster preparedness and mitigation. Among the uncertain factors, condition of lifelines carries special importance for the effectiveness of time-critical response activities. Damage to infrastructure, especially to highways and roads, adversely affects accessibility to disaster areas [5]. For pre-disaster logistics planning, preparedness and mitigation activities, it is important to predict the post-disaster condition of the road network at a system level. For instance, this information can be utilized in optimization models in order to generate more robust and reliable planning decisions.

We study the problem of locating emergency response facilities (ERFs, in short) as part of disaster preparedness strategies. The ERFs, where durable relief items are positioned before a disaster, serve as coordination and supply points for the distribution of relief items after a disaster. Relief item requirements throughout the disaster area are represented by demand points with estimated weights. Distribution of the items from ERFs to demand points is carried on a road network, whose node set consists of demand points, potential ERF locations and main junctions in the highway system. The links of the network represent the connections with respect to the paths in the highway system. We define our problem such that links in the network may fail during the disaster because of building collapses and/or road damages; hence, may be unavailable for the distribution of the relief items to casualty areas. For rapid disaster response, it is desired to have an ERF located sufficiently close to each demand point in the surviving network. However, this may not be possible for each demand point due to link failures. Therefore, we focus on determining the number and locations of ERFs to be used in case of a disaster so that a maximum proportion of the demand can be satisfied in reasonable time.

We formulate a stochastic integer programming model that determines the locations of ERFs among a set of potential ones with the objective of maximizing expected total demand covered within a predetermined distance parameter, over all possible network realizations. In the first stage, before a disaster occurs, facilities are located under uncertainty. In the second stage, after a disaster has occurred and a surviving network is realized, total demand covered by the open facilities is computed by a path-based approach. For this purpose, we consider a pre-determined

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set of alternative paths between each pair of potential facility-demand nodes so that the shortest surviving path can be used for relief item distribution.

In this setting, each link may randomly be in either operable (surviving) or non-operable (failed) status after the disaster. Hence, these links jointly form a random network whose possible outcomes are extremely large in number even when a small number of links exist. Main challenges in solving the resulting stochastic program are the vast number of outcomes (i.e., scenarios) and assessing their likelihoods. Our study differs from the stochastic emergency facility location literature in coping with these two challenges. We calculate individual link survival probabilities according to their vulnerability to a potential disaster and establish an implicit joint probability distribution while generating a sample of network scenarios randomly. In generating a scenario, we consider both spatial proximity and the vulnerability ordering among the links, and propose a new distance-based dependency model for creating correlated link failures. As a practical solution approach, we resort to a tabu search heuristic that estimates the objective function value of the candidate solutions by sample average approximation. By this way, we can explore a large sample of scenarios in short computation time.

With no doubt, it is difficult to predict which network links would fail/survive in a specific disaster situation. Nevertheless, damage risk can be assessed for road segments considering the vulnerable structures and the hazard risk of the area. However, we need to translate this link-level information to the network level by a systematic approach. It is unlikely that link failures would be independent of each other as a disaster impacts the structures within a local area in similar destructive capacity and the area possesses similar characteristics. Considering this, we propose a practical method for simulating distance-dependent correlation between link failures under an expected disaster scenario. To support our proposition, we note Tobler's [45] first law of geography: “Everything is related to everything else, but near things are more related than distant things”. This precept leads to useful quantitative techniques for analyzing correlation relative to distance or connectivity relationships in geographic research [32]. We adopt this concept of spatial dependence to model the functionality of an infrastructure network in a disaster-prone region and demonstrate its use in facility location decisions and how the service levels can be improved by such an approach by means of the Istanbul case study. We solved a large scale problem having around 10,000 links using our tabu search algorithm with a sample of 10,000 network scenarios generated according to the proposed distance-based link failure model. We compare the obtained solutions to those obtained by (i) no link failure, and (ii) independent link failures. We analyze various parameter settings to quantify the significance of incorporating dependent link failures in a large scale real-life problem.

The remainder of the paper is organized as follows. In Section 2, we compare our study with similar work in the literature. We describe the problem in Section 3 and the proposed solution approach in Section 4. In Sections 5 and 6, we provide the application of our approach to Istanbul's earthquake preparedness case. A summary of our results and possible extensions are presented in Section 7.

2. Literature review

Facility location problems for responding to large-scale emergency incidents and disasters have been studied with increasing interest in the literature. Caunhye et al. [6] give a recent review of optimization models in emergency logistics, including a brief discussion on the contents of facility location studies. Anaya-Arenas et al. [3] present the characteristics of location problems studied until 2012 in conjunction with network design and transportation decisions for relief distribution. Here, we review studies related to facility location in the pre-disaster stage with respect to our proposed methodology. The relevant publications can be classified as those that employ a deterministic model versus those considering uncertainty.

Deterministic models usually address problems for specific regions prone to different types of disasters. Dekle et al. [8] study identification of disaster recovery center (DRC) locations for the state of Florida, under hurricane threat, with the aim of minimizing the total number of DRCs while covering county residents within a distance limit. In their two-stage solution process, first stage finds DRC locations by considering the distance limit and the second stage improves the solution of the first stage in terms of transportation convenience and building safety. Cheng and Tzeng [7] propose a fuzzy multi-objective model for designing a relief delivery system for Taiwan. Görmez et al. [19] address an emergency response facility (ERF) location problem in Istanbul metropolitan area where a destructive earthquake is expected to occur. Their objective is to minimize both the number of opened ERFs and the weighted average distance between demand points and their closest opened ERFs. They model a two-tier distribution system and consider both capacitated and uncapacitated ERFs, as well as distance limits and backup facility requirements with respect to regional vulnerability. According to their results, a small number of ERFs is sufficient to distribute relief items after a potential earthquake. In this paper, we address the case of Istanbul using a different objective and model uncertainty in road failure conditions.

In preparation for effective disaster response, Duran et al. [10] propose a mixed-integer programming inventory location model in order to pre-position emergency items at warehouses worldwide for CARE (Cooperative for Assistance and Relief Everywhere International) organization with the objective of minimizing the response time from open warehouses to the demand points. They analyze the effect of the required number of facilities and their inventory levels on the average response time, and test the robustness of the results using simulation techniques. In a recent study, Abounacer et al. [1] provide a multi-objective location-transportation problem with capacity and multiple resource constraints. The objectives are to minimize the total transportation time, the number of responders needed to open and operate the facilities, and the total uncovered demand. They present an epsilon-constraint method that generates the exact Pareto front. They also provide a method that does not generate all Pareto optimal solutions but runs faster in generated test instances.

There are several studies in the literature that consider uncertainty in demand quantities, supply availability and transportation network capacity. Most of these studies employ a scenario-based approach in a stochastic programming framework, where some of them take the network condition fixed. Jia et al. [24] propose to generalize the covering, p-median and p-center models under a set of possible emergency scenarios. Scenarios are defined by means of demand amounts and the service capability of each facility, which is reduced by the level of disruption. The aim is to minimize the regret across all emergency scenarios. Balçık and Beamon [4] study an ERF location problem in which the relief items are classified with respect to their response time criticalities and ERFs have capacity limits for holding each item type. They present a scenario-based model that determines the number and locations of ERFs and their optimum inventory levels to maximize the satisfied demand of relief item types. The scenarios represent the uncertainties in disaster locations and demand quantities. Doyen et al. [9] introduce a two-stage model to determine the locations of pre- and post-disaster rescue centers, the amount of relief items to be stocked and their transportation decisions under uncertain demand and transportation times. In their computational study,