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Bi-objective bilevel optimization of distribution center locations considering user equilibria

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ABSTRACT

We propose a bi-objective, bilevel optimization model for the location of relief distribution centers (DCs) in humanitarian logistics. The upper-level decision-maker (an aid-providing organization) selects locations for capacitated DCs. On the lower level, beneficiaries choose a DC according to distance and amount of supply to be expected. This effects a user equilibrium on the lower decision level. Upper level objectives are to minimize total opening cost for the DCs and total uncovered demand. We develop an exact algorithm for determining the Pareto frontier of the problem, integrating the adaptive epsilon-constraint method, a branch-and-bound procedure, and the Frank–Wolfe procedure.

1. Introduction

In the literature on facility location, much attention has been devoted to the optimal choice of facilities or distribution centers where customers are supplied with products, commodities or services of different kind. These centers should be positioned close enough to the places where the customers live, such that distances to be traveled by customers are not prohibitive. On the other hand, opening a too large set of centers incurs too high costs, and this must be avoided as well. Typically, centers have assigned capacities, which imposes further restrictions on the organization of the supply.

In the present paper, a particular problem of this type arising in humanitarian logistics shall be addressed. Similar problems may also occur in other areas such as health care management, service logistics or telecommunications. The characteristic feature of the present problem formulation is that we assume distribution centers to be subject to possible *congestion effects*. As a consequence, customers choose the centers not only based on the distance criterion, but also based on their expectations with respect to supply limitations. We assume that the choice behavior of the customers can be represented by a *user equilibrium model*. A combination of decisions of several persons who jointly use a set of resources is called a user equilibrium (UE) if no user can gain by unilaterally changing her/his decision.

The paradigmatic application of our model addresses the supply of victims of a natural disaster by relief commodities in the response phase of disaster management. Natural disasters as earthquakes, floods, hurricanes, etc. can have a devastating impact on a region and can cause immense suffering to people. Humanitarian logistics (see Van Wassenhove, 2006; Tomasini and Wassenhove, 2009) contributes to alleviate the consequences of disasters. Because of destroyed infrastructure, the affected population often needs help in the form of relief goods as food, drinkable water, clothes, medicine or similar. The problem of last-mile distribution of such relief goods has been intensely studied in the recent literature (see, among others,

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Bozorgi-Amiri et al., 2013; Hentenryck et al., 2010; Rath and Gutjahr, 2014; Sheu, 2007; Tricoire et al., 2012; Vitoriano et al., 2011). The best-possible location of distribution center (DCs) lies at the core of this problem. Typically, it is supposed that the beneficiaries walk to a nearby DC in order to obtain the relief commodities. Several optimization models have been developed to support the decision on the location of the DCs by a quantitative approach. However, most of these models either assume that beneficiaries always choose the nearest opened DC, or that the aid provider can control their allocation to DCs. As it shall be argued, there are many cases where both assumptions are unrealistic.

The present work formulates a bi-objective bilevel optimization model with coverage and cost as the objective functions on the upper decision level, and a user equilibrium resulting from individual cost minimization (concerning costs for travelling and uncovered demand) on the lower decision level. In the humanitarian logistics application, the decision maker (DM) of the upper level, the "leader" in the terminology of bilevel programming, is an aid-providing organization, and the DMs of the lower level, the "followers", are the beneficiaries. We develop a technique for the exact solution of the model in the sense of the determination of the Pareto frontier of the bi-objective problem. The technique uses the epsilon-constraint method and employs a branch-and-bound procedure for the upper-level decision. The lower-level UE is determined by means of the Frank–Wolfe algorithm. A numerical example with real-world data from the province Thiès in Senegal illustrates the approach. Furthermore, the UE is also extended to a stochastic user equilibrium (SUE) to represent the case of imperfect information.

The paper is organized as follows: Section 2 outlines related literature. In Section 3, the model is described in formal terms. Section 4 presents our proposed solution algorithm. In Section 5, some experimental results are reported. Section 6 extends the UE model to a SUE model. Section 7 provides some specific observations from experiments as well as policy implications, and the concluding Section 8 summarizes the achieved results and outlines topics for further research.

2. Related literature

In the area of disaster management, bilevel optimization models involving user equilibria have been proposed mainly, but not exclusively, for evacuation planning. Only very few articles deal with commodity distribution, the topic of the present paper. Let us start by mentioning some works on evacuation planning.

Kongsomsaksakul et al. (2005) build on the combined distribution and assignment (CDA) problem (see, e.g., Evans (1976); Lundgren and Patriksson (1998)) in order to optimize emergency evacuation to shelters. The leader is the authority determining the shelter locations, the followers are the evacuees. The objective function is total evacuation time. The route choice by the evacuees within the traffic network is predicted based on Wardrop's equilibrium model. Shelters are capacitated, and it is assumed that the total demand arriving at a shelter cannot exceed the shelter capacity. The model is solved heuristically by a genetic algorithm.

Shen et al. (2008) deal with a similar evacuation problem as that of Kongsomsaksakul et al. (2005), but they elaborate their model within a stochastic optimization context, taking possible disruptions of links in the traffic network into account. The leader determines the location of the safety shelters, and the followers (the evacuees) choose between the multiple routes connecting node-shelter pairs. Shelters are assumed to have unlimited capacities. Again, the objective function corresponds to the evacuation time (the maximum travel time over all node-shelter pairs under the UE), but it is now reformulated to a regret function based on the chosen stochastic model. For the solution of the model, the authors apply a genetic algorithm using as a subprocedure the Frank–Wolfe algorithm for the determination of the UE.

Kulshrestha et al. (2011) develop a robust bilevel programming formulation based on a CDA model where the network traffic is assumed to be in a UE and where for the selection of shelters, a logit model is used. The upper-level objective function is total cost for establishing and operating the shelters. A cutting plane algorithm is used to solve the resulting problem. Finally, Li et al. (2012) address hurricane evacuation and propose a stochastic bilevel optimization model for shelter location where the route choices are assumed to form a dynamic UE.

Let us turn now to articles addressing commodity distribution rather than evacuation planning. Sun et al. (2008) develop a bilevel programming model for the location of DCs. The leader, minimizing a cost objective function, is the planner who determines where to open DCs. The followers are customers who choose among the DCs, taking congestion effects into account. As in Kongsomsaksakul et al. (2005), DCs are capacitated and the demand arriving at a DC cannot exceed its capacity. A simple tailored heuristic algorithm is used to solve the problem.

Camacho-Vallejo et al. (2014) develop a bilevel programming model for humanitarian logistics. Therein, the leader is the country affected by a disaster. The leader's decision is on the distribution and the means of transportation of relief commodities within the own territory to the places in need; the objective function represents response time. The follower is the community of countries or international organizations providing help by delivering the relief commodities. The follower's decision is on the quantities of each commodity shipped from each country or organization by each mode of transportation to each storage center in the affected country; the follower's objective function represents cost. The bilevel optimization model does not involve a UE on the lower level. It is solved exactly by means of dualization on the lower level. Also a bi-objective consideration is hinted by setting the leader's objective function against the follower's objective function. The authors report on a case study for Chile.

In Camacho-Vallejo et al. (2014), a bilevel uncapacitated facility location problem is tackled where the leader chooses the locations with a cost objective in mind, and the followers (customers) choose between opened facilities according to preferences. No UE model is involved. The problem is solved by means of an evolutionary algorithm.