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A Two-echelon joint continuous-discrete location model

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ABSTRACT

The problem of locating up to a given number of facilities in continuous Euclidean space that can serve as intermediate transshipment points between multiple stakeholders in a supply chain — suppliers and customers — who are distributed over the same space is considered. The first contribution is in considering the multisource Weber problem (MWP) in the presence of both source points and demand points rather than either alone. The second contribution is that the selection of intermediate facilities for further discrete analysis is based on a quantitative determination rather than a subjective selection process, which is typical of most popular commercial-grade mathematical programming (LP and IP) based location models. While the mathematical programming approach benefits from a degree of richness in features and a sense of computational optimization, one limitation is that the candidate locations to be evaluated must be specified, often without any computational basis for them. Computational experiments on randomly generated problem instances and real case studies indicate that significant gains can be achieved with relatively little effort by expanding the boundary of analysis to include multiple suppliers and multiple customers in the analysis and design of a supply chain network. An alternating location-allocation-type heuristic method is developed that is easy to implement. The third contribution is the development of two different lower bounding procedures that demonstrate the high quality of this obtained heuristic solution.

1. Introduction

Facility location modeling has been an important tool for assisting in the location of commercial facilities throughout the supply chain network such as warehouses, plants, distribution centers, cross docks, ports, break-bulk terminals, service centers, and public stations (fire, police, and ambulance). In this paper, the problem of locating up to a given number of facilities that serve as intermediate transshipment points between a set of suppliers, or supply points, and a set of customers, or demand points is considered. Each customer demands a certain amount of a single product that should be sourced from a single facility. (However, the case where multi-facility sourcing is allowed is also considered.) There is assumed to be enough supply among the suppliers to satisfy total demand. The locations of the supply points and demand points in Euclidean space are specified. Facility locations need to be determined so that the overall costs are minimized. The facilities can be located anywhere within the continuous Euclidean space. The Euclidean space is divided into zones that have specific fixed facility costs and specific outbound transportation costs. The economic role of such intermediate transshipment points lies in their ability to benefit from transportation cost economies. Such points also help in consolidation or break-bulk strategies. The facilities that are to be located can be of a variety of specific types — warehouses, intermediate plants, cross docks, service facilities, repair facilities, amongst others. Assumption of single sourcing is made only for customers and not for facilities, as in many problem contexts, customers are relatively smaller retailers. In such situations single sourcing is usually preferred on account of ease and convenience of operations and additional administrative overhead incurred to coordinate across accounting and marketing systems in case of multiple sourcing (refer Geoffrion & Graves, 1974). Multiple sourcing is usually not a concern at the intermediate facility locations since such locations are primarily used for large volume transhipments in multiple products from multiple suppliers. To

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facilitate this, there is heavy investment in sophisticated inbound and outbound coordination mechanisms.

In the remainder of this section, the extant literature on location problems and how the problem considered in this paper relates to these are studied.

Location models have been studied for a long time in economics, marketing, engineering and operations research areas. Refer to Brandeau and Chiu (1989); Drezner (1995) and Drezner and Hamacher (2002) for surveys on location problems. There are different classification frameworks for location problems. The most relevant for the purposes of this paper are *discrete* and *continuous* location problems. Most of the models considered in the literature focus on facility location selection from amongst a finite given set of candidate locations. Such problems are called discrete location problems.

Some of the representative work on discrete location problems are highlighted. In all these models, there is an underlying network. Supply points and demand points are nodes on this network. There are different classes of discrete facility location problems. These classes include set covering, maximal covering, p-center, p-median, p-dispersion, fixed charge, hub and maxisum location problems. A measure of distance (in many cases this is related to travel time and service level) in some form or other is fundamental to all such models. A variety of objective functions are considered. These include minimizing the number of facilities, minimizing the cost of facilities and related service costs, minimizing the maximum distance to a demand point, etc. An early work in discrete facility location is Geoffrion and Graves (1974). The authors consider the problem of choosing appropriate facilities to open from amongst a given finite set of facilities. Multiple commodities are transported and there are lower and upper bounds on the total throughput of an open facility. Recently, models have been developed that consider the joint problem of simultaneously deciding which facilities to open and what size they should be. The sizing could be related to the staffing or inventory level at facilities so as to provide a given service level to demand points assigned to the facility. Refer to Shen, Coullard, and Daskin (2003) and Venkateshan, Mathur, and Ballou (2010) for such models. All these models, however, presuppose a finite set of candidate facilities as an input to the problem. Refer to Current, Daskin, and Schilling (2002) for a survey of discrete location problems. Note that if the number of candidate facilities is finite and fixed and there is no distinction between supply and demand points, the problem considered in this paper reduces to the p-median problem (see Mirchandani & Francis, 1990). Models that explicitly include two different levels of interaction, such as supply point-intermediate facility and intermediate facility-demand point, have been referred to in literature as hierarchical location models. A variety of authors (Geoffrion and Graves, 1974 and Hindi and Basta, 1994 amongst others) have developed specialized algorithms for such problems. See Klose and Drexl (2005) and Şahin and Süral (2007) for recent reviews. While two-level models have been considered in a discrete facility location context, research addressing continuous hierarchical location problems – which is the focus of the present work – is relatively lesser. See Kocaman, Huh, and Modi (2012) for an application of continuous hierarchical facility location in locating transformers and power distribution network design.

The types of problems encountered in continuous location are now noted. The Weber problem seeks the location of a single facility that minimizes the weighted distances from given demand points. Exact solution procedures for the Weber problem involve an iterative procedure that successively approaches the optimal solution. See, for instance, Cooper (1968); Ostresh et al. (1978) and Vardi and Zhang (2001). Other single facility location approaches include graphical techniques (see Weber 1909) and approximation methods (see Wesolowsky & Love, 1972).

When location of more than one facility (as is considered in this paper) is required, the problem becomes more complex, since the objective function is neither convex nor concave (See Cooper 1967.) This problem is called the multisource Weber problem (MWP). Exact solution procedures for the MWP include the branch-and-bound methods developed by Kuenne and Soland (1972), Ostresh (1973), Ostresh et al. (1975), Drezner (1984) and Rosing (1992), the set reduction and p-Median algorithm of Love and Morris (1975), the dynamic programming based method of Love (1976) and Brimberg and Love (1998) and the difference-of-convex programming method of Chen, Hansen, Jaumard, and Tuy (1998). These methods have been capable of solving relatively smaller-sized problems. Recently column-generation-based algorithms for solving the MWP have been developed that are capable of solving larger-sized problems. (See Krau 1997 and Righini and Zaniboni, 2007.) A variety of heuristic solution approaches have also been developed for the MWP. These include the sequential location-allocation procedure of Cooper (1964), local search methods (see Love and Juel, 1982 and Brimberg & Mladenovic, 1996b), modifications of the objective function methods (Chen 1983), methods based on clustering (Sullivan & Peters, 1980, Moreno, Rodriguez, & Jimenez, 1990), a projection method (Bongartz, Calamai, & Conn, 1994), Tabu search (Brimberg & Mladenovic, 1996a) and neural networks (Aras, Özkisacik, & Altinel, 2006). Continuous location problems in the presence of fixed costs is considered in Brimberg, Mladenovic, and Salhi (2004) and Brimberg and Salhi (2005). A comparative study of various methods to solve the MWP can be found in Brimberg, Hansen, Mladenovic, and Taillard (2000). A survey of the MWP and its various generalizations and solution procedures can be found in Drezner et al. (2002). More recent references include Laporte, Nickel, and Gama (2015) and Melo, Nickel, and Gama (2009). The problem in this paper is more restrictive than the uncapacitated MWP discussed above. The restriction arises since each demand point has to be matched by a supply point. Some of the other constrained MWPs in literature are capacitated MWPs. In these problems, there is an upper bound on the total customer demand that can be satisfied by a facility. See, for instance, Zainuddin and Salhi (2007) and Martino, Salhi, and Nagy (2009).

The implicit assumption in the uncapacitated or capacitated MWP is that any facility so located has sufficient supply of commodities to cater to demand points assigned to it. How this supply can be obtained and the associated costs are not considered in the MWP. The focus in MWP, therefore, is on optimizing the costs associated with only one echelon in the supply chain. The problem in this paper considers an additional echelon in the supply chain by explicitly accounting for the availability of supply and locates facilities that balance the overall costs. A facility necessarily has to be assigned to at least one supply point and to at least one demand point and the total supply to a facility must equal the total demand satisfied by it.

2. Model

For the two-echelon MWP (2EMWP), the notation used in the paper is listed.

Inputs:

m upper limit on the number of facilities to locate
J total number of supply points, $j = 1, \dots, J$
SUP_j available supply at jth supply point, assumed integer
(X_j^S, Y_j^S) location of the jth supply point on the Euclidean plane
K total number of demand points, $k = 1, \dots, K$
DEM_k required demand at kth demand point, assumed integer