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A distance-limited continuous location-allocation problem for spatial planning of decentralized systems

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ABSTRACT

We introduce a new continuous location-allocation problem where the facilities have both a fixed opening cost and a coverage distance limitation. The problem has wide applications especially in the spatial planning of water and/or energy access networks where the coverage distance might be associated with the physical loss constraints. We formulate a mixed integer quadratically constrained problem (MIQCP) under the Euclidean distance setting and present a three-stage heuristic algorithm for its solution: In the first stage, we solve a planar set covering problem (PSCP) under the distance limitation. In the second stage, we solve a discrete version of the proposed problem where the set of candidate locations for the facilities is formed by the union of the set of demand points and the set of locations in the PSCP solution. Finally, in the third stage, we apply a modified Weiszfeld's algorithm with projections that we propose to incorporate the coverage distance component of our problem for fine-tuning the discrete space solutions in the continuous space. We perform numerical experiments on three example data sets from the literature to demonstrate the performance of the suggested heuristic method.

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1. Introduction

Source location and allocation problems are the essential components of strategic planning for sustainable development. Many problems have been studied to help decision making in this area. Some of these studies included a list of predetermined candidate locations to locate source facilities, thus solved site-selecting location problems in a discrete space. Greenfield development problems, however, involves undeveloped sites that have no existing infrastructure and the facilities can be located at any point on a continuous space. This type of facility location problems are known as the site-generating problems (Love et al., 1988).

Motivated by the popularity of the decentralized systems in the energy and the water access networks, in this paper, we study a site-generating location-allocation problem for greenfield infrastructure planning. Our aim is to determine the number and the locations of the source facilities, which can be, for example, a solar or a wind power generation system or a water pump serving demand points as a stand-alone system. Assuming that the energy or the water resource availability is even over the field, the location-allocation decisions are made based on the spatial locations of the demand points. Our objective is to minimize the sum of the facility opening costs, which are independent of the locations of the facilities, and the connection costs to serve demand points such as cable or pipe installation costs that are linearly increasing in the distances to the serving facilities. All facilities are assumed to be uncapacitated; however, they can only serve demand points within a specified distance. This coverage distance limitation of the facilities can be associated with the constraints on the voltage drop in the energy systems (due to the resistance on cables) as in Kocaman et al. (2012) or the pressure loss in the water systems (due to the friction in the pipes) as in Douglas et al. (1979) that are both linearly increasing with distance.

We present and study a continuous location-allocation problem with a fixed facility opening cost and a limit on the coverage distance of the facilities. This problem is related to three well-known problems in the literature: the planar set covering problem (PSCP), the uncapacitated multi-source Weber problem (MWP), and the simple plant location problem (SPLP). In the special case, where there is no connection costs between the demand points and their serving facilities, our problem reduces to the PSCP. The original set covering problem (SCP) considers a finite collection of sets and their costs, and determines the lowest cost sub-collection whose union equals the union of the collection. This problem is known to be an NP-hard problem (Garey and Johnson, 1979). Several exact (Balas and Carrera, 1996; Beasley, 1987; Beasley and K.Jörnsten, 1992; Fisher and Kedia, 1990) and heuristic (Beasley, 1990; Beasley and Chu, 1996; Caprara et al., 1999; Haddadi, 1997; Lorena and Lopes, 1994) methods are proposed to solve the SCP that have

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applications in fields such as crew scheduling (e.g., Caprara et al., 1999) and locating emergency facilities (e.g., Rajagopalan et al., 2008; Toregas et al., 1971). The algorithms for the SCP are compared in the survey paper (Caprara et al., 2000) by Caprara et al. After the turn of the century, the work on the SCP concentrate on heuristic algorithms based on greedy randomized search (Bautista and Pereira, 2007; Haouari and Chaouachi, 2002; Lan et al., 2007), local search (Yagiura et al., 2006), genetic algorithm (Solar et al., 2002) and ant colony optimization (Ren et al., 2010). The PSCP problem considers a finite number of demand points in the Euclidean space and determines the minimum number of facilities and their locations in the plane such that each demand point is within a certain distance to at least one of these facilities. To solve the PSCP exactly, Church (1984) defined the circle intersection points set (CIPS) as the locations of all demand points and the intersection points of all circles centered at the demand points with a radius of a predetermined coverage distance. Then, for each point in the CIPS, a set is formed of all demand points that are within the coverage distance from the point. Considering the collection of all these sets, the original version of the SCP is solved. It is possible to show that there exists at least one optimal solution to the PSCP in which all facilities are located in the CIPS (Eiselt and Sandblom, 2013).

The MWP is a site-generating location-allocation problem, which is also known as the continuous p-median problem. It locates p facilities in the Euclidean plane to serve a finite set of demand points, each having an associated weight. In this problem, each demand point is served by the closest facility and the objective is to minimize the weighted sum of the distances to the closest facilities. The MWP is known to be an NP-hard problem (Megiddo and Supowit, 1984); therefore, several heuristic solution methods are proposed in the literature. Cooper's iterative location-allocation algorithm (Cooper, 1963; 1964) is a well-known algorithm developed for this problem. Starting at an arbitrary solution that divides the set of demand points into p almost-equal-sized subsets, the algorithm alternates between location and allocation steps until a local optimal solution is found. In the allocation step, for fixed locations of the facilities, algorithm simply assigns each demand point to its nearest facility (breaking ties arbitrarily), and once the allocations are fixed, in the location step, the problem reduces to p independent single facility location problems that can be solved by the modified Weiszfeld's method in Vardi and Zhang (2001). As the final solution depends on the initial solution, a random multi-start version of this algorithm can be applied as in Drezner et al. (2016). Another line of work is based on the idea of starting at a good initial solution. Based on the observation that the optimal solution of the continuous problem often has several facilities co-located with the demand points, in Hansen et al. (1998) proposed the p-median heuristic. This heuristic first solves the p-median problem, which chooses p facility locations from the set of demand points to minimize the weighted sum of distances. Then, p independent single facility location problems are solved as in the location step of the Cooper's algorithm. Recently, Brimberg and Drezner (2013) proposed to overlay the area containing the demand points with a grid. Then, a p-median problem is solved over the nodes of the grid to obtain high-quality starting points for the Cooper's algorithm. Since there is a significant correlation between the qualities of the initial and the final solutions, starting at the p-median solution improves the algorithm results. Brimberg et al. (2014) proposed an alternating solution procedure where a local search is conducted in the continuous space to obtain a local optimum. The locations from the continuous problem solution is then augmented in the discrete space problem, which is solved again to obtain new initial points for the continuous space problem. This process continues until no further improvement is observed. Finally, Drezner et al. (2015) developed a distribution-based variable neighborhood search and a genetic algorithm, and a hybrid algorithm that combines these two approaches. The hybrid approach outperformed both approaches. For other heuristic, metaheuristic and exact approaches for the MWP, readers can refer to a comprehensive review by Brimberg et al. (2008).

The SPLP is a problem in a discrete space, where there are fixed facility opening costs and a finite set of possible locations for the facilities. It aims to minimize the sum of the facility opening costs and the weighted connection costs. The adjective “simple” in its name is to state that the facilities are uncapacitated. This problem is widely studied in the literature. Krarup and Pruzan (1983) provided a highly cited survey on this problem. It is stated in that paper that the SPLP is also an NP-hard problem. The version of SPLP with distance constraints also appeared in the literature. Berman and Yang (1991) introduced the problem and proposed an iterative algorithm starting from the solution of the uncapacitated facility location problem. Krysta and Solis-Oba. (2001) and Weng (2013) presented integer programming (IP) formulations for the unweighted problem and proposed approximation algorithms. The work on the continuous space version of the SPLP, however, is very limited. Brimberg et al. (2004) introduced the fixed cost for facilities that is independent of the location. The problem that we consider in this paper reduces to the problem considered in Brimberg et al. (2004) if the coverage distance limitation is removed. They proposed a multi-stage heuristic approach for the problem without the coverage constraint. Following the path in Hansen et al. (1998) of solving the discrete version to obtain an initial solution for the continuous problem, in the first stage of this heuristic, the SPLP is solved assuming that the demand points are the potential locations for facilities. Then, in the second stage, a fine tuning is performed in the continuous space using Weiszfeld's method. Brimberg and Salhi (2005) introduced zone-dependent fixed costs for the facilities, where they defined zones as polygons. An efficient exact solution algorithm for the single facility case was proposed, whereas, for the multi-facility case, they proposed heuristic procedures.

Drezner et al. (1991) introduced a Weber problem with limited distances. In that problem, the cost for a demand point increases linearly with its distance from the facility until a limit is reached. Afterwards, the cost stays constant at the limiting value. A possible motivation for this problem is that, after a distance limit, the service to demand points may be provided with an alternative method. In that case, the distance limit can be viewed as a break-even point on the cost. In the distance-limited continuous location-allocation problem that we present, as opposed to the constant cost after the distance limit in Drezner et al. (1991), we assume an infinite cost after the distance limit, so our problem is quite different than other distance-limited problems considered in the literature (e.g. in Drezner et al., 2016; 1991; Fernandes et al., 2014).

In our problem, the number of facilities to be opened is a decision variable. For a given number of facilities and without a distance limitation, our problem becomes the MWP, which is NP-hard. We propose a multi-stage heuristic solution method, in which we solve the discrete version of the problem and then adjust facility locations in the continuous space for fine-tuning. The final solution quality highly depends on the initial solution quality we obtain from the discrete version of the problem. Employing the demand points as the only possible locations for the facilities (as is done in Brimberg et al., 2004; Brimberg and Salhi, 2005; and Hansen et al., 1998) would limit the solution quality of the discrete problem. Augmenting this set of possible locations with a small number of additional promising locations is the main idea presented in this paper. Rather than overlaying the area of demand points by a fine grid, as is done in Brimberg and Drezner (2013), we propose

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