European Journal of Operational Research 236 (2014) 957–967

Contents lists available at ScienceDirect

European Journal of Operational Research

journal homepage: www.elsevier.com/locate/ejor

Lower and upper bounds for a two-stage capacitated facility location problem with handling costs

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ARTICLE INFO

Article history:
Available online 28 October 2013

Keywords:
Facility location
Heuristic
Dantzig–Wolfe decomposition
Path relinking

ABSTRACT

We study in this paper multi-product facility location problem in a two-stage supply chain in which plants have production limitation, potential depots have limited storage capacity and customer demands must be satisfied by plants via depots. In the paper, handling cost for batch process in depots is considered in a realistic way by a set of capacitated handling modules. Each module can be regards as alliance of equipment and manpower. The problem is to locate depots, choose appropriate handling modules and to determine the product flows from the plants, opened depots to customers with the objective to minimize total location, handling and transportation costs. For the problem, we developed a hybrid method. The initial lower and upper bounds are provided by applying a Lagrangean based on local search heuristic. Then a weighted Dantzig–Wolfe decomposition and path-relinking combined method are proposed to improve obtained bounds. Numerical experiments on 350 randomly generated instances demonstrate our method can provide high quality solution with gaps below 2%.

1. Introduction

As a key topic in the design of transportation systems (Brandeau & Chiu, 1989), facility location problems (FLPs) have appealed to both researchers and practitioners for more than 40 years. A basic FLP, already NP-hard, is the uncapacitated FLP (UFLP), which consists in locating uncapacitated facilities, such as plants, depots or warehouses, and defining the amount shipped by open facilities to customers, in order to minimize the sum of the set-up costs of the open facilities and of the distribution costs. A natural extension is to take into account the maximum demand of each facility could supply, giving the capacitated facility location problem (CFLP) (Cornuejols, Sridharan, & Thizy, 1991; Klose & Görtz, 2007). A special case of CFLP met in distribution networks is the single source CFLP (Ahuja, Orlin, Pallottino, Scaparra, & Scutellà, 2004; Contreras & Díaz, 2008) or concentrator problem, in which each customer must be served by only one facility. More complicated versions of the CFLP include the dynamic CFLP, defined on a multiperiod horizon (Dias, Captivo, & Clímaco, 2007; Melo, Nickel, & Saldanha da Gama, 2006), and the stochastic CFLP in which demands and supplies can be random variables (Lin, 2009; Wang, Batta, & Rump, 2002).

All problems cited above consider one product and a simple network with two layers of nodes (also called levels) or, equivalently, one distribution step (also called stage or echelon). Although such networks exist, most supply chains are more complex and involve several products, more than two levels (e.g., plants, depots and customers), and inter-level products. The development of operations research and computers have made possible the study of facility location problems in supply chains, called *hierarchical facility location problems*, see for instance the recent review of Şahin and Süral (2007).

Hierarchical facility location problems (HFLPs) is an extension of the CFLP by taking into account more than one echelons in the distribution network. A set of customers are usually laid at the last echelon, while various type of facilities are modeled for other echelons. The product flow traverses all echelons successively. The two-stage facility location problem (TSFLP) (Keskin & Üster, 2007a, 2007b; Klose, 1999, 2000; Martí & Pelegrín, 1999;

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http://dx.doi.org/10.1016/j.ejor.2013.10.047

Tragantalerngsak, Holt, & Rönnqvist, 1997), with two types of facilities, is a basic model of HFLP. Products supplied by plants are delivered to capacitated depots, and then distributed to customers aiming at minimizing both shipment costs and the fixed opening costs of depots. Several variants were derived from the TSFLP, for instance by locating plants and depots (Elhedhli & Gzara, 2008; Pirkul & Jayaraman, 1996, 1998) and by considering four layers composed of suppliers, plants, depots and customers (Jayaraman & Pirkul, 2001). In this paper, our attention focuses on the TSFLP.

The objective function of the TSFLP comprises both shipment costs and investment costs induced by opening depots. Investment costs, regarded as the strategic decision level, are much more important than shipment costs in practice. Therefore it is common to consider a reference period (e.g., quarter of a year), and let both shipment costs and investment costs including the overhead and amortization costs be modeled over this period. Besides the investment costs incurred by location decision and the operational shipment costs, the costs on handling products at depots cannot be negligible, specially in the food supply chain. The cargo must be unloaded, sorted, packaged, reloaded and dispatched after entering into depots. As this treatment of cargo involves tasks accomplished by both workers and machines, such as palletizers, forklifts and conveyors, it is common to regard it as capital and labor intensive process (Newton, Barnhart, & Vance, 1998). Efficiently using handling costs can save costs and bring profits for companies. Thus, the handling costs are significant parts of overall costs in the distribution system, and introducing them into the TSFLP seems reasonable and realistic.

Two types of handling costs are considered in this paper: the cost for handling one unit of product and the bulk cost for processing a batch of products. Considering the first type of cost is not hard in the classical model of facility location problems, since it can be incorporated into the unit shipment cost on arcs starting from the depot. The bulk cost under special working situations is however not easy to integrate into the shipment cost, due to the facts that the number of workers assigned to the batch, their qualifications, the equipment used, etc. To describe handling costs in a understandable and realistic way, we retake the concept of *handling modules* proposed by Li et al. (2011). In the paper, a pre-given alliance of workers and equipment (e.g., a set of palletizers with their drivers), having both handling capacity and handling cost during a reference period, is modeled as one handling module. The handling capacity represents the maximum amount of cargo which can be treated over the reference period. The handling cost consists of the normal depreciation of equipment, employment costs of workers, etc. The handling cost per handling module and per cross-docking task is totally charged once the module is used to handle cargo, even for a small portion of its capacity. Thus, efficiently using module capacity leads to a smaller handling cost per product unit.

Li et al. (2011) considered a two stage capacity location problem with handling cost (TSCFLP-HC) and cross-docking tasks. In our preliminary work (Li et al., 2011) of the TSCFLP-HC, a limited set of different types of handling module are equipped at each depot. The decision on depot location, product flow and the number of handling modules *per type and per cross-docking task* must be made, with the goal of minimizing the total depot opening, transportation and handling cost. The problem was formulated by a linear mathematical programming. However, the problem proposed by Li et al. (2011) takes into account cross-docking tasks, which pertain basically to detailed operational tasks, and unrealistic to be considered in the strategic level of facility location problem. The work in this paper is the extension of our precedent work. We proposed in this paper a mathematical model making a slight difference in comparison with the one of Li et al. (2011), since the facility location problem considered in this paper takes into account handling module in the strategic and tactical level decision, without the detailed operational level decision–cross-docking tasks. Therefore the work is a variant of TSCFLP-HC (Li et al., 2011).

To derive an initial lower bound, Li et al. (2011) proposed a subgradient optimization procedure based on Lagrangean relaxation, and use a simple heuristic to provide an initial upper bound from each lower bound obtained. The heuristic repaired each lower bound by opening depots where handling modules are used, or randomly closing DCs iteratively until the minimum number is reached. In this paper, we proposed a local search heuristic based on the information provided by subgradient optimization, which concerns ADD/DROP/SWAP moves. The advantage of the local search heuristic is to avoid local optimum and provide good initial upper bound for further improvement with subsequent advanced approach.

The paper brings two academic contributions. The first contribution is to provide initial upper bound with a local search heuristic algorithm based on the lower bound provided by subgradient optimization procedure. The second one consists in improving lower and upper bounds by using a weighted Dantzig–Wolfe decomposition, and reinforced by a path-relinking. To evaluate the performance of the proposed method, 350 randomly generated instances are tested.

The remainder of the article is organized as follows. In Section 2, the TSCFLP-HC is defined in details and formulated as a mixed linear program. Section 3 describes the main blocks of the hybrid solution method: the Lagrangean relaxation with its subgradient optimization procedure, the column generation process and the post-optimization based on path-relinking. A set of instances and computational results are presented in Section 4. Some conclusions are drawn and future research is discussed in Section 5.

2. Problem formulation

The proposed TSCFLP-HC is defined on a three layers with a set I of plants, a set J of potential depots, a set K of customers and a set P of different products. Each plant $i \in I$ has a production limitation s_i^p of each product $p \in P$. Each potential depot $j \in J$ has an opening cost g_j and a limited capacity c_j. Each product $p \in P$ occupies a volume per unit denoted as υ^p.

When products arrive at a depot, they are processed by handling modules. Let M_j represent the set of module types available at each depot $j \in J$. It is worth noting that the set of modules are different for each depot. Each type $m \in M_j$ of handling module at depot $j \in J$ is characterized by a handling capacity q_j^m and a cost b_j^m. u_j^m corresponds to the number of modules available at each potential depot $j \in J$. The cost of a module is counted as soon as it is used, even for a fraction of its capacity.

The non-negative demand of each product $p \in P$ for each customer $k \in K$ is denoted by d_p^k. The total volume of all demands is represented by $d(K) = \sum_{p \in P} \sum_{k \in K} \upsilon^p d_k^p$. The unit transportation cost of product $p \in P$ from depot $j \in J$ to customer $k \in K$ is denoted by h_{jk}^p. Similarly, h_{ij}^p represents the cost of shipping one unit of product $p \in P$ from plant $i \in I$ to depot $j \in J$. Three sets of variables are considered: binary variables Y_j are equal to 1 if depot j is opened, non-negative integer variables Z_j^m represent the number of handling modules of type $m \in M$ used at depot $j \in J$, and real variables X_{ij}^p and X_{jk}^p defining the flow of products from plants to