Computers & Industrial Engineering 110 (2017) 307–321

Contents lists available at ScienceDirect

Computers & Industrial Engineering

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

A multi-period facility location problem with modular capacity adjustments and flexible demand fulfillment

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ARTICLE INFO

Article history:
Received 29 November 2016
Received in revised form 12 April 2017
Accepted 5 June 2017
Available online 9 June 2017

Keywords:
Facility location
Multi-period
Capacity expansion and contraction
Delivery lateness
Mixed-integer linear models

ABSTRACT

We consider a multi-period facility location problem that takes into account changing trends in customer demands and costs. To this end, new facilities can be established at pre-specified potential locations and initially existing facilities can be closed over a planning horizon. Furthermore, facilities operate with modular capacities that can be expanded or contracted over multiple periods. A distinctive feature of our problem is that two customer segments are considered with different sensitivity to delivery lead times. Customers in the first segment require timely demand satisfaction, whereas customers in the second segment tolerate late deliveries. A tardiness penalty cost is incurred to each unit of demand that is satisfied with delay. We propose two alternative mixed-integer linear formulations to redesign the facility network over the planning horizon at minimum cost. Additional inequalities are developed to enhance the original formulations. A computational study is performed with randomly generated instances and using a general-purpose solver. Useful insights are derived from analyzing the impact of several parameters on network redesign decisions and on the overall cost, such as different demand patterns and varying values for the maximum delivery delay tolerated by individual customers.

1. Introduction

In today's globally competitive market, firms are faced with an increasing need to improve their flexibility, reliability, and responsiveness to satisfy the demands of their customers. In order to meet these challenges, it is crucial for firms to be able to adjust the configuration of their facility networks to changing market conditions. Important enablers include opening new facilities in markets with high demand growth and closing facilities in regions with demand decline. In addition, capacity scalability, i.e. adding or removing capacity to/from facilities, is also a meaningful strategy to adequately respond to fluctuations in the level of market demand.

In this study, we address a facility network that needs to be redesigned in order to effectively serve predicted variations in demand over time. To this end, gradual changes in the network structure and in the capacities of the facilities are considered over a planning horizon which is assumed to be finite and divided into several periods. The objective is to determine the minimal cost schedule for facility opening, facility closure, capacity expansion, and capacity contraction, and to allocate customer demands to operating facilities over time. A distinctive feature of the problem that we study is that customers are differentiated according to their sensitivity to delivery lead times. Customers having zero lead times require their demands to be satisfied in the time period they occur. Customers tolerating late deliveries specify a positive maximum delivery lead time. Delivery after the preferred due date and not beyond the latest acceptable time period is permitted, but incurs a tardiness penalty cost that depends on the length of delay. Customer segmentation on the basis of preferred delivery lead times can be encountered in various industries. Wang, Cohen, and Zheng (2002) describe the case of a semiconductor equipment manufacturer that provides a two-class service policy for repairable parts. Customers with emergency demand pay a premium price to have their returned defective parts promptly repaired. Non-emergency service is provided to all other customers who accept a longer repair time in exchange for a lower price. This type of policy is also termed "demand postponement" by Wu and Wu (2015) because the firm decides upon the actual delivery time for orders committed to customers who are less sensitive to lead times.

Integrated planning for facility location and capacity sizing under flexible conditions for demand fulfillment gives firms a framework to handle dynamic situations when significant changes in demand (and costs) over time are anticipated. Our work makes

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http://dx.doi.org/10.1016/j.cie.2017.06.003
0360-8352/

an important contribution toward the development of mathematical models to support the underlying decision-making process. From an economic viewpoint, the temporary adjustment of the capacity of an existing facility, either through expansion or contraction, may be more advantageous than installing a new facility in some other location or even closing the existing facility. However, trade-offs must be made between investments on facility location, capacity scalability, distribution costs, and tardiness costs for delayed demand satisfaction. We note that our problem arises in the context of sizing decisions being reversible in the medium term. This is the case, for example, when space and equipment can be rented or leased.

The contribution of our study is threefold. First, we address a new multi-period facility location problem which extends a particular case recently examined by Correia and Melo (2016). Second, we develop two alternative mixed-integer linear programming (MILP) formulations. One is a natural way of formulating the problem using specific sets of binary variables to represent facility location and capacity scalability decisions. The other is inspired by a modeling framework recently introduced by Jena, Cordeau, and Gendron (2015) and uses a single set of binary variables to capture all capacity transitions that occur at each particular location between two consecutive periods. The formulations strongly differ in the number of binary variables. We also describe various enhancements to the two formulations to improve the bound provided by their linear relaxations. In recent years, general-purpose MILP solvers have become an effective and reliable tool for solving many (real-world) problems. However, the capability of a solver to produce good, potentially optimal, solutions within acceptable computing time greatly depends on the selection of the right model. Therefore, the third contribution of our work is to perform a comparative analysis of the proposed formulations by using a state-of-the-art MILP solver. For this purpose, a large set of instances was randomly generated exhibiting different demand patterns. Important managerial insights will be provided on how delivery lead time restrictions affect the configuration of an existing facility system, the overall cost of redesign decisions, and the capacity usage of operating facilities.

The remainder of this paper is organized as follows. Section 2 gives a brief review of related literature. In Section 3, the problem that we study is formally described and two alternative MILP formulations are proposed. Various classes of additional inequalities are introduced in Section 4 for both formulations. The results of an extensive computational study are discussed in Section 5. Finally, Section 6 presents concluding remarks and outlines opportunities for further research.

2. Related research

In the multi-period (or "dynamic") facility location problem (MFLP), the objective is to determine the spatial distribution of facilities at each time period of a finite planning horizon so as to minimize the total fixed and variable costs for meeting customer demands over time. This natural extension of the single period or static version of the discrete location problem is particularly suited to handle situations with predicted changes in the parameters of the problem. If a network is already in place with a number of facilities being operated at fixed locations then location decisions also comprise the phase-out of initially existing facilities. Jacobsen (1990, chap. 4) and, more recently, Nickel and Saldanha da Gama (2015, chap. 11), discuss basic modeling aspects and address several variants of the MFLP.

Multi-period facility location has been a field of recurring interest as demonstrated by the surveys by Arabani and Farahani (2012), Klose and Drexl (2005), and Owen and Daskin (1998). In this section, we provide a review of the literature on the MFLP with a focus on the development of models that capture at least one of the main characteristics of our problem, namely, modular capacity scalability of facilities and flexible demand fulfillment.

2.1. MFLP with modular capacity acquisition

When market demand growth is anticipated and the capacities of existing facilities will not be sufficient to handle future customer requirements, firms face decisions about where and how to expand their capacities. This form of capacity scalability was addressed by Lee and Luss (1987) and, more recently, by Julka, Baines, Tjahjono, Lendermann, and Vitanov (2007). Although in earlier works the location of facilities was not included in the decision set, the importance of integrating capacity acquisition decisions with facility location decisions has been widely recognized. In this case, the choice of the amount of capacity to be installed at a particular facility is often made by selecting a capacity level from a finite set of options. As argued by Correia and Captivo (2006), this is an assumption with practical relevance since capacity is often purchased in the form of equipment which is only available in a few discrete sizes. Moreover, fixed and operating facility costs are frequently subject to economies of scale that depend on the capacity choices.

The MFLP with modular capacity expansion has been addressed by various authors. Syam (2000) analyzes facility location and sizing decisions for an international firm and considers three levels of capacity expansion. At each location, capacity can be increased over successive time periods within the planning horizon. Gourdin and Klopfenstein (2008) also examined the problem of progressively expanding an existing telecommunications network through installing modular equipment over time. Delmelle, Thill, Peeters, and Thomas (2014) proposed a model for redesigning a network of educational facilities through opening new schools and closing existing schools. The latter decision can be made on the condition that the school has reached a certain age. The student capacity of a school can also be raised by installing additional mobile units, each having the same size, for which leasing costs are incurred. Location and capacity acquisition decisions are constrained by an available total school budget over the planning horizon. Recently, Correia, Melo, and Saldanha-da-Gama (2013) described a MILP model for the design of a two-echelon network. New facilities are established in the upper and intermediate echelons of the network and their capacities are gradually extended through the installation of storage areas dedicated to families of products. In particular, the same type of storage area can be selected more than once for a given family over the planning horizon. Cortinhal, Lopes, and Melo (2015) also studied a multi-stage supply chain network redesign problem with location and capacity decisions. Modular capacity expansions can occur at a particular location as long as the overall capacity does not exceed a pre-specified global size. The problem examined by Shulman (1991) differs from the works discussed before in that multiple facilities of different types can be established at a given location. This situation arises in the design of telecommunications networks where the facilities represent various kinds of concentrators. At each time period, at most one facility of each type can be selected at a particular site but several facilities can be opened if they are of different types. This scheme is employed to gradually adjust the operating capacity of the facility network.

2.2. MFLP with modular capacity expansion and contraction

In a multi-period setting it may also be meaningful to dispose of capacity during periods of declining demand. Therefore, capacity scalability does not only focus on expanding capacity but also