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Competitive facility location on decentralized supply chains

Qiang Meng *, Yikai Huang, Ruey Long Cheu

Department of Civil Engineering, National University of Singapore, Singapore 117576, Singapore

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ABSTRACT

This paper addresses a novel competitive facility location problem about a firm that intends to enter an existing decentralized supply chain comprised of three tiers of players with competition: manufacturers, retailers and consumers. It first proposes a variational inequality for the supply chain network equilibrium model with production capacity constraints, and then employs the logarithmic-quadratic proximal prediction–correction method as a solution algorithm. Based on this model, this paper develops a generic mathematical program with equilibrium constraints for the competitive facility location problem, which can simultaneously determine facility locations of the entering firm and the production levels of these facilities so as to optimize an objective. Subsequently, a hybrid genetic algorithm that incorporates with the logarithmic-quadratic proximal prediction–correction method is developed for solving the proposed mathematical program with an equilibrium constraint. Finally, this paper carries out some numerical examples to evaluate proposed models and solution algorithms.

1. Introduction

Locating facilities to produce a kind of product and determining their production levels, which is referred to as the facility location problem here, are the strategic level decision problems for a firm to design its supply chain with the incentive of profit maximization. Facility location decisions may be the most critical and most difficult of the decisions needed to realize an efficient supply chain because inefficient locations for production will result in excess costs being incurred throughout the lifetime of facilities, no matter how the production plants, transportation options, inventory management, and information sharing decisions are optimized in response to changing conditions. A rich and vast literature has been developed on the subject of facility location over the years accordingly (see, e.g., Daskin et al., 2005 and the references therein). The majority of facility location problems assume that the locating facility is either a price taker or a monopolist, so that the market competition among manufacturing facilities is neglected. Even for the integrated location/inventory and location/routing models that may include the third-party logistics service providers (e.g., Laporte, 1988; Min et al., 1998; Nozick and Turnquist, 1998; Nozick, 2001; Shen et al., 2003), analysis of competition is too simple.

When a firm locates a new manufacturing facility, and begins producing and shipping products to demand markets, this typically stimulates certain reactions on the markets. For example, the introduction of a new facility increases the overall capacity of an industry, and hence can perturb the established economic equilibrium status of supplies, demands and product flows, which is actually a long-term steady market state due to competition. The introduction of this new capacity, and in the case of an "entering" firm, the introduction of an entirely new competitor on the market, will trigger some form of competitive response from existing firms in the industry. This would suggest that to truly make a profit maximizing location decision, the firm must anticipate the market's reaction to a potential location decision, in its actual location decision-making process. Inspired by Hansen and Thisse (1977) as well as Erlenkotter (1977) and Tobin and Friesz (1986) thus proposed the competitive facility location issue that is able to quantitatively take into account the market competition to some extent. In reality, their work has extended the scope of facility location studies. They developed a generalized bilevel programming model for the competitive facility location problem, in which the lower level problem is the spatial price equilibrium (SPE) model (see, Nagurney, 1999) that characterizes the economic equilibrium state of the market in response to the facility location decision of an entering firm, which is a steady result of the market competition. After a series of explorations in depth (Friesz et al., 1988, 1989; Miller et al., 1992), Miller et al. (1996) contributed a monograph on the competitive facility location problems with SPE constraints, and pointed out that bilevel programming models and sensitivity analysis based heuristic methods can provide a solution to the competitive facility location problem.

* Corresponding author. Tel.: +65 6516 5494; fax: +65 6779 1635.
E-mail address: cvemq@nus.edu.sg (Q. Meng).

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Although the SPE model can quantify the supply and demand equilibrium conditions, it is incompetent on capturing economic equilibrium conditions of a supply chain comprising manufacturers, retailers and consumers with free-market competition. Such a supply chain involving different decision-makers is cast as the decentralized supply chain in the literature (Lee and Billington, 1993; Lederer and Li, 1997). As such, a novel and interesting research issue regarding the competitive facility location on the decentralized supply chains has emerged. The main objective of this paper is to build a mathematical model and design a solution algorithm for the competitive facility location problem of the decentralized supply chain.

Prior to modeling the proposed competitive facility location problem, it is a prerequisite to seek economic equilibrium conditions induced by the market competition in the decentralized supply chains. With respect to a kind of product, manufacturers, retailers and consumers are three kinds of independent decision-makers or players in a decentralized supply chain with the free-market competition mechanisms. They can be logically represented by a three-tier network according to their decision. Manufacturers in the first tier make decisions on the production levels and price the finished products so as to maximize their own profits. Retailers in the second tier, in turn, agree with shipments of the product shipped from the manufacturers, and maximize their profits by publishing appropriate selling prices to the consumers. Consumers in the third tier purchase the product by weighing the price they are willing to pay as well as the induced transaction cost. It is well known that Nash noncooperative game-theoretical framework can perfectly describe the economic behaviors of manufacturers and retailers in maximizing their respective profits, and the SPE model is capable of capturing the behavior of consumers distributed on the different demand markets, in consuming the product. Therefore, Nagurney et al. (2002) remarkably proposed the supply chain network equilibrium (SCNE) model, formulated by a variational inequality (VI), for investigating the economic behaviors of the players in a decentralized supply chain with the market competition. They claimed that after competition, the supply chain would obtain an economic equilibrium state. Their model can find the equilibrium shipment and price patterns between manufacturers and retailers, which will become necessary inputs in modeling the competitive facility location problem on the decentralized supply chains. It should be further pointed out that the seminal paper by Nagurney et al. (2002) has triggered a variety of studies on the SCNE models. For example, the SCNE model with random demands (Dong et al., 2004), the multitiered network equilibrium model for reverse supply chain management and electronic waste recycling (Nagurney and Toyasaki, 2005), the multitiered supply chain network model with electronic commerce and demand side risk (Nagurney et al., 2005), unconstrained minimization formulations for the SCNE models (Meng et al., 2007). Besides, the competitive equilibrium analysis for the players in a decentralized supply chains has been received more attention recently (Walsh and Wellman, 2003; Savaskan, 2004; Wang et al., 2004).

Any manufacturing facility, in fact, should have the production capacity constraint, i.e., a limit on the amount of the product produced during a time period, due to the limited resources, especially for the preceding competitive facility location problem on the decentralized supply chain. This paper will first propose the SCNE model with production capacity constraints formulated as a VI because these practical constraints are neglected in Nagurney et al. (2002). Having considered the production capacity constraints, the equilibrium price pattern between manufacturers and retailers includes the optimal Lagrangian multipliers with respect to these constraints. As a consequence, the production capacity constraints induces ineffectiveness of the modified projection method suggested by Nagurney et al. (2002) when solving the VI of the SCNE model with the production capacity constraints. Fortunately, a novel logarithmic-quadratic proximal prediction–correction (LQP P–C) method developed by He et al. (2006) can be employed for solving the corresponding VI. Moreover, it can find the optimal Lagrangian multipliers with respect to the production capacity constraints, which are necessitated in investigating the competitive facility location problem.

After successfully deriving the SCNE model with production capacity constraints, this paper proceeds to build a generic mathematical program with equilibrium constraints (MPEC) model for the competitive facility location problem on the decentralized supply chain. The proposed MPEC model involves binary (0–1) decision variables representing whether or not a candidate site is chosen and the parameterized VI constraint that formulates the SCNE model with the production capacity constraints in the case of a given feasible facility location solution. It can be seen that the proposed MPEC model is flexible because users can define their objective functions and constraints while modeling a specific competitive facility location problem. Note that the MPEC approach has already been used to study various optimization problems that have arisen from transportation research and management science (Luo et al., 1996; Outrata et al., 1998). Nevertheless, the proposed MPEC model is a combinational optimization problem (i.e., the discrete optimization problem) with the time-complexity of NP-complete. From mathematical programming point of view, the MPEC model is a variation of the integer programming problem. However, some traditional analytical solution methods, such as the branch-and-bound or branch-and-cut method, developed for the integer programming problems are not available for solving the MPEC model due to the parameterized VI constraint. Thus, we have to seek for a heuristic solution method for the generic MPEC model.

Genetic algorithms (GAs) (Goldberg, 1989) are adaptive meta-heuristic search algorithm premised on the evolutionary ideas of natural selection and genetic. The basic concept of GAs is designed to simulate processes in natural system necessary for evolution, specifically those that follow the principles first laid down by Charles Darwin of survival of the fittest. As such they represent an intelligent exploitation of a random search within a defined search space to solve a problem. First pioneered by John Holland in the 1960s (Holland, 1975), GAs have been widely studied, experimented and applied for solving the hard problems such as the genetic MPEC model, which arises in engineering, business and management science (Winter et al., 1995). Not only does GA provide the alternative methods to solve problem, it consistently outperforms other traditional methods in most of the problems link. It can be seen that the proposed MPEC model has two unique characteristics: binary decision variables and solution of the parameterized VI constraint and at any given facility location solution can be evaluated by the LQP P–C method. These two properties indicate that a hybrid GA embedded with LQP P–C method is fit for solving the MPEC model. This is because the string of the binary decision variables straightforwardly forms a chromosome and the LQP P–C method can be employed as a subroutine in evaluating the fitness function for the hybrid GA. Besides GAs, it should be pointed out that the other meta-heuristic methods including Tabu search (Glover, 1986) and simulated annealing (Kirkpatrick et al., 1983) can be also employed as the solution methods for the MPEC model.

The remainder of the paper is organized as follows. Section 2 will present the VI of the SCNE model with the production capacity constraints, and will elaborate the LQP P–C method as well. Section 3 will give the MPEC model for the competitive facility location problem on the decentralized supply chains. Section 4 illustrates the hybrid GA incorporating LQP P–C method. Section 5 carries out numerical examples to demonstrate the methodology proposed. Finally, conclusions are presented in Section 6.