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Design and operation of a two-level supply chain for production-time-dependent products using Lagrangian relaxation

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ABSTRACT

We consider a design and operation problem of a two-level supply chain of a poultry company. The supply chain consists of a number of (candidate) suppliers and one manufacturing plant. Each supplier, if established or opened, produces semi-finished products and delivers them to the manufacturing plant that produces finished products to satisfy dynamic demand. In each supplier, production times of different types of semi-finished products are different, but production of those semi-finished products should be started at the same time if they are in the same process batch, although they may be completed at different times. The problem considered in this paper is to determine whether to establish suppliers among candidates at the beginning of the planning horizon for operation during the planning horizon and to determine production plans of the suppliers with the objective of minimizing the sum of transportation costs and production costs as well as establishment cost of the suppliers. We present a mixed integer programming model, and develop a heuristic algorithm based on Lagrangian relaxation. Performance of the algorithm is evaluated through a series of computational experiments on randomly generated instances based on data from a poultry company in Korea and results are reported.

1. Introduction

In this paper, we consider a supply chain design and production planning problem of a two-level supply chain modeled from a poultry company in Korea. The supply chain consists of a manufacturing plant and multiple suppliers. There are several candidate locations for (establishment of) the suppliers, but the location of the manufacturing plant, which is already established, is given. Each supplier, if established, produces several types of semi-finished products which are used to produce finished products at the manufacturing plant. In each (candidate) supplier, there is a single production line, in which all types of semi-finished products can be produced. After being produced by the suppliers, the semi-finished products are delivered to the manufacturing plant, where (finished) products are produced. By using the information of demand, which is known but varies period by period, the company determines the establishment (opening) of candidate suppliers at the beginning of the planning horizon and the production quantity in each period at each established supplier.

In the poultry farming company considered in this study, there are a few types of chickens (semi-finished product types) produced in poultry farms (suppliers) and the chickens are distinguished by the weights. The weights of the chickens usually depend on the raising time (production time) in the farms. Therefore, (semi-finished) product types are distinguished by the production time. We call products with such characteristics *production-time-dependent products*. (The characteristics of production-time-dependent products can also be seen in a cleaning process in semi-conductor manufacturing systems, in which wafers are processed in batches.) Also, on hygienic grounds (for cleaning and disinfection of the farm) and for ease of management such as control of amount of feeds, breeding of chicken in the same batch is started simultaneously. In other words, a set of chickens is started to be raised at the same time and a subset of them is delivered to the plant earlier than the others, while these others are raised for more time for bigger products. Moreover, farms prepare to produce all types of chickens when they start production of a new batch. The reason is that it is easier to respond to changes of the production plan by modifying production quantities of each type of chicken than by adding a new production batch.

We consider a system in which all suppliers and the manufacturing plant are under the control of a managing unit (of a company). There are two decisions to be made in the system of poultry farming, which are determination of (the locations of) suppliers that are to be established at the beginning of the planning

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horizon and will be operated during the planning horizon among candidate locations and determination of the production quantities of the semi-finished product types at the established suppliers in each period. In this paper, we consider a problem with these two decisions, which is called the *supply chain design and production planning problem for production-time-dependent products* (SCDPP-TDP).

To the best of our knowledge, there has been no research, or very few at most, on this problem, SCDPP-TDP, and it seems that this is a first attempt to consider a system in the poultry farming industry. The problem considered in this paper, SCDPP-TDP, is related to the facility location problem (FLP). If the length of the planning horizon and the processing time is one period, the number of product types is one, production cost of each product is 0, and capacities of all suppliers are infinite, SCDPP-TDP is reduced to the uncapacitated facility location problem (UFLP). Note that since the UFLP is known to be NP-hard (Cornuejols, Nemhauser, & Wolsey, 1990), SCDPP-TDP is also NP-hard.

There are many previous studies related to facility location problems. For instance, Erlenkotter (1978) suggests a dual-based procedure for an uncapacitated facility location problem, and Neebe and Rao (1983) present a branch-and-bound algorithm for a capacitated facility location problem with a single source. Also, Cho (2001) suggests a column generation approach to a capacitated facility location problem. In addition, Geoffrion and McBride (1978), Christofides and Beasley (1983), Barcelo and Casanovas (1984), and Klincewocz and Luss (1986) present Lagrangian based heuristic algorithms, Min, Ko, and Ko (2006), Suzuki and Yamamoto (2012), and Fernandes et al. (2014) suggest genetic algorithms, while Rolland, Schilling, and Current (1997), Salho (2002), and Shishebori, Dayarian, Jabbarzadeh, and Barzinpour (2014) suggest tabu search algorithms for capacitated facility location problems.

Also, SCDPP-TDP is related with the dynamic-demand facility location problem (DFLP) in that both problems are concerned with determining locations of facilities to satisfy dynamic demand. However, in the typical DFLP, they consider cases of a single product type or multiple types of products which are processed independently, while in the problem considered in the study, semi-finished products are processed in batches at a supplier. Also, in the typical DFLP, production time of products is not considered (or assumed to be negligibly short compared to the length of a period), while in our problem it is assumed that production times for different semi-finished product types are different and are longer than the length of a period.

Since the research of Wesolowsky (1973), facility location problems with multi-period dynamic demand have been considered by many researchers. There are two types of models for the problems. One is a model in which inventories are allowed in each period during the planning horizon, and the other is a model in which inventories at the end of each period are limited to be zero, as in this paper. There are a few research results on the model with zero inventory at the end of each period. Wesolowsky (1973), Wesolowsky and Truscott (1975), and Sweeney and Tatham (1976) present optimal solution algorithms based on dynamic programming, and Van Roy and Erlenkotter (1982), and Canel and Khumawala (1997) develop a branch-and-bound algorithm. There also have been many heuristic algorithms. Chardaire, Sutter, and Costa (1996) suggest heuristic algorithms based on Lagrangean relaxation and simulated annealing. On the other hand, Torres-Soto and Üster (2011) additionally consider the capacity limit of each facility and develop an optimal solution algorithm and a heuristic algorithm for the problem.

The supply chain network design problem (SCNDP) is also related to our problem (SCDPP-TDP) in that both problems are concerned with design of a network for transporting products from plants to demand sites (retailers or customers). Since a model of Geoffrion and Graves (1974), various mathematical models for the SCNDP have been suggested in a number of articles, such as those of Cohen and Lee (1989), Cohen and Moon (1991), and Beamon (1999). Also, Dogan and Goetschalckx (1999), Cordeau, Pasin, and Solomon (2006), and Bidhandi, Yusuff, Ahmad, and Bakar (2009) develop optimal solution algorithms to solve large-size problems using Bender's decomposition method, while Cohen and Lee (1989), Tanonkou, Benyoucef, and Xie (2008), Costa, França, Paulo, and Filho (2011), Badri, Bashiri, and Hejazi (2013), Pan and Nagi (2013), and Kumar and Tiwari (2013) develop heuristic algorithms for solving large-size problems in a reasonably short time. However, in existing studies on SCNDPs they only consider cases with a single-period demand, or constant demand rate, which are unrealistic.

Multi-level production planning problems are also related to SCDPP-TDP. Among research articles on those problems, Jacob and Khumawala (1982) and Roll and Karni (1991) suggest mathematical formulations for multi-level uncapacitated lot sizing problem. In addition, Lin and Chen (2007) suggest a mathematical model for a multi-stage and multi-site production planning problem. Also, Tempelmeier and Helber (1994) suggest a heuristic algorithm to solve a dynamic lot sizing problem with capacitated constraints, and Pasad and Krishnaiah Chetty (2001), Tempelmeier and Buschkühl (2009), and Zegordi, Kamal Abadi, and Beheshti Nia (2010) suggest heuristic algorithms for multi-level production planning problems.

In this paper, we develop a Lagrangian-relaxation heuristic for the SCDPP-TDP. In the heuristic algorithm, the problem is solved in two steps: determining the location of the facilities, i.e., determining which suppliers are to be established at the beginning of the planning horizon and to select suppliers to start processing a production batch (operated) in each period, and then determining the production quantities in each period of the planning horizon for each semi-finished product type at the selected suppliers.

The remainder of this paper is organized as follows. In the next section, we describe the problem considered in this paper in detail and give a mixed integer programming formulation for the problem. Then, we present a heuristic algorithm, and it is evaluated through a series of computational experiments. Finally, we conclude the paper with a short summary and discussions on possible extensions.

2. Problem description

We consider a supply chain design and production planning problem for production-time-dependent products (SCDPP-TDP) in a two-level supply chain which consists of multiple (candidate) suppliers and a manufacturing plant. In the SCDPP-TDP, the decision on the establishment (opening) of a supplier is identical to the decision on the determination of locations of the suppliers to be established from candidates. There are a number of candidate locations for the suppliers, and suppliers to be established at these candidate locations have different capacities, fixed costs for establishment, production costs, and transportation costs to the manufacturing plant, which are given and known. In the problem, we determine (locations of) the suppliers to be established in a way that minimizes the costs related to the locations of the suppliers (fixed, production, and transportation costs). In this study, we determine whether to establish each (candidate) supplier at the beginning of the planning horizon and production quantities of semi-finished product types at the established suppliers in each period during the planning horizon.