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Product distribution via a bi-level programming approach: Algorithms and a case study in municipal waste system

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ABSTRACT

The design of distribution network influences the performance of supply chain systems. A well-designed distribution network can help a supply chain system to achieve maximum profits or minimize total cost. In this work, algorithms are designed to allocate customer demands to the distribution centers (DCs) in the supply chain network. The best locations for DCs and production distributions through DC in this work are found via a bi-level programming model. The upper-level model under the firm's consideration is to determine the optimal locations for DCs and allocate supplies to minimize the total cost, while the lower-level model is to minimize the total transportation cost of all customers. In this work, the demands of customer (or the demands of DC) can be split among DCs (or plants). Propositions for optimal assignment are presented where supplies cannot be split. All 5 algorithms are proposed to solve each level of the problem. The priorities in allocating process in each algorithm are different, taking into account the structure of the problem. The effectiveness of these algorithms are compared with the optimal/best solutions found using CPLEX and an existing algorithm. The simulation results show that all of the proposed algorithms are superior to CPLEX in large-scale problems. The proposed algorithms can execute up to 4200 DCs and 4200 customers while CPLEX can execute only problems up to 500 × 500 in size. Experiments are done to solve the municipal waste system (3,211 demand nodes and up to 48 DCs) covering 5 provinces of Northern Thailand.

1. Introduction

A supply chain is defined as an integrated process comprising procurement, production and distribution processes, whose purposes are to get raw materials from suppliers, convert raw materials to products at the factory and then deliver the final products to retailers or customers. The objective of supply chain management (SCM) is to maximize the profit of all processes in the system. All flows of information, products or money in a supply chain are important factors determining its efficiency. Optimal management of these flows is therefore key to supply chain success. Decisions related to these flows can be categorized into 3 phases—strategies or designs, plans and operations. In this work, we are interested in the strategy part, which balances efficiency and responsiveness in supply chain. Distribution center problem is part of facility location problem, which involves the locations of distribution centers (DCs) and the allocation of customer demands to DCs.

Facility locations and allocations of demands to facilities are topics of wide interest in logistics research. Basic location models are summarized in Aikens (1985) as uncapacitated and capacitated facility location models, and stochastic demand and dynamic capacitated facility location models. The objective functions of all models are to minimize the transportation costs and the fixed cost of locating a facility. Research works on stochastic and dynamic facility location problems during 1964–1997 are reviewed by Owen and Daskin (1988). The dynamic models attempt to locate facilities over time. Stochastic location problems consist of 2 approaches: probabilistic and scenario planning. Input parameters for these models are assumed to be uncertain. Logistic system in supply chain comprises 2 main parts: plants to DCs and DCs to customers. Geoffrion and Graves (1974) were among the first researchers to separate distribution problems into 2 sub-problems using benders decomposition. Pirkul and Jayaraman (1998) suggested capacitated plant and warehouse models with multi-commodity. They proposed a heuristic approach based on Lagrangian relaxation for mixed integer programming. Hindi, Basta, and Pienkosz (1998) proposed branch and bound algorithm for multi-commodity 2-stage distribution problem assuming that each customer must be fully served by only 1 DC. As the allocation of customers to multiple distribution centers with constraint to balance product flows in all DCs is an NP-hard problem, Zhou, Min, and Gen (2002) offered a genetic algorithm approach to solve this problem. Many firms save structure and start-up costs when new

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facilities are built using cross-docking DCs. Products are transported to a cross-docking DC and spread out to the customers without handing in the inventory. In 2003, Jayaraman and Ross (2003) suggested a simulated annealing approach for a cross-docking DC in the supply chain. Sharma, Moon, and Bae (2008) proposed an analytic hierarchy process with multi-criteria to optimize distribution network with relevant choices for decision-maker. More recently, a hybrid planning algorithm for the distribution center problem was proposed by Lee and Kwon (2010). They proposed a heuristic based on tabu search and decomposition optimization. In 2013, Tsao (2013) considered distribution center problem under trade credits. A continuous approximation method is used to formulate the model which integrates facility cost, inventory cost, transportation cost and ordering cost.

Bi-level programming problems are hierarchical optimization problems where the constraints of one problem (or upper-level problem) are obtained by another optimization problem (or lower-level problem). Stackelberg problems have a hierarchical structure similar to bi-level programming, but the lower-level is to find an equilibrium rather than an optimal solution. Bi-level program was initially defined by Bracken and McGill (1973) as *a mathematical program with optimization in the constraints.* Bi-level programming is difficult to solve because even the simplest case is an NP-hard problem (Ben-Ayed, 1993; Jeroslow, 1985). Non-convexity of bi-level programming is an additional cause for its difficulty (Ben-Ayed, 1993); even when both upper and lower-level problem are convex, the whole problem is not guaranteed to be convex. Various algorithms have been developed to solve bi-level programming problem including the "*k*th best" algorithm proposed by Bialas and Karwan (1983), grid-search algorithm by Bard (1983), implicit enumeration by Candler and Townsley (1982), branch and bound algorithm by Bard and Moore (1990), penalty function method by White and Anadalingam (1993), a genetic algorithm by Mathieu, Pittard, and Anadalingam (1994) and penalty function based on Kuhn-Tucker condition by Lv, Hu, Wang, and Wan (2007).

Although facility location problems have been widely studied, little attention has been given to bi-level programming. Only in 1999 did Taniguchi, Noritake, Yamada, and Izumitani (1999) develop a bi-level programming model to optimize capacity and location of cross-docking distribution centers. Since upper-level problem is a nonlinear problem on a large scale, a genetic algorithm was proposed for this problem. Huang and Liu (2004) suggested a bi-level programming model to optimize a logistic distribution network with balanced workload requirement in the lower level with the proposed genetic algorithm. Later, a heuristic based on a special form of constraints for bi-level model was proposed to estimate the response function between two levels (Sun, Gao, & Wu, 2008). Yang (2012) proposed a layer iterative method to solve bi-level programming in supply chain distribution problem using existing optimization algorithm. Zhang and Xu (2014) also considered the problem in bi-level programming with uncertain customer demands and continuous cost function in the lower level. They used the existing method to solve the problem in each level with the sample size up to 44 suppliers and 23 DCs. Zhang, Li, Qian, and Cai (2014) considered supply chain networks with bidirectional flows. They applied Lagrangian relaxation to the linearized nonlinear objective function and found the upper and lower bound of the problems. Their computational success is up to 120 DCs, 120 suppliers and 120 customers. Diabat, Battaia, and Nazzal (2015) studied a single-level supply chain from a single plant to DCs and from DCs to retailers. The simulation problems solved are up to 200 DCs and 250 retailers. They widened the gaps between upper and lower bounds to reduce the processing time.

In the real world, customers choose the service or products from DCs by their behaviors and benefits. After that, the firm's planners predict the locations of DC based on the customers' requirements. As mentioned above, the system has 2 different decision makers where their needs/interests are different but not independent of one another. In this paper, therefore, the distribution center problem is represented by the bi-level programming model. The purpose of bi-level programming model is to find the optimal location and product flow for each DC. The upper- and lower-level models are to determine the optimal location by minimizing the firm's total cost, and to minimize the customers' total transportation cost, respectively. An example of this system is the transportation of an agricultural product or agricultural waste.

In a typical Thai farm, farmers either deliver their products or wastes to a distribution center themselves or pre-sell their products to a middleman who takes care of the deliveries in the system. If supplies cannot be divided among DCs, the problems are considered simple under some specific assumptions. In such a scenario, an optimum assignment can be given. For more complicated problems, where supplies can be split, 5 proposed algorithms are presented to solve the lower-level problem in bi-level programming to minimize the total transport cost of customers, which is the cost of transferring their products to DCs by themselves. The case with the middleman will not be considered in this study due to the difference in the nature of the problem, which involves Traveling Salesman Problem (TSP). All proposed algorithms are tested on 24 combinations of number of DCs and customers, with 100 random data sets in lower-level problems. An illustrative example in this work is to find the locations for municipal waste storage and to allocate customer's demand to storage sites in 5 provinces in Northern Thailand. Actual 2012 data sets of municipal waste system in 5 provinces of Northern Thailand collected by Dantrakul, Likasiri, and Pongvuthithum (2014) are used in this paper. The objective function values of an illustrative example obtained by our proposed algorithms are compared with the objective function value from the best of the 3 methods in that work, and also with the optimal value obtained from CPLEX.

This paper is organized as follows: Section 2 introduces the information of bi-level programming approach and formulates the model for upper-level and lower-level problems and also sequential propositions and definitions for an optimum assignment. In Section 3, our 5 proposed algorithms for the lower-level part are described in details. Computational simulations are presented in Section 4 to demonstrate the effectiveness of the proposed algorithms via comparisons with the optimal solution from CPLEX. In Section 5, an illustrative example based on the municipal waste management in 5 provinces of Northern Thailand is solved by all 5 proposed algorithms and compared with the optimal solution from CPLEX and with an existing work. Finally, computational results are discussed in Section 6.

2. Model development

2.1. Bi-level programming problems

Bi-level programming involves the interaction between two decision makers. A general formula of bi-level programming problem is as follows:

$$(U)\quad \underset{x}{Min}\quad F(x, y(x))$$
$$\text{s.t.}\quad G(x, y(x)) \le 0,$$

where $y(x)$ is implicitly solved by

$$(\text{L})\quad \underset{y}{Min}\quad f(x, y)$$
$$\text{s.t.}\quad g(x, y) \le 0,$$

Model U is the upper-level problem and model L is the lower-level problem. The main characteristic of bi-level programming problem is that the solution of the lower optimization problem is considered as a constraint in the upper optimization problem. In the model, $F(x, y(x))$ and $f(x, y)$ are the objective functions of upper- and lower-level decision makers, respectively. $G(x, y)$ and $g(x, y)$ are the