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A restricted dynamic model for refuse collection network design in reverse logistics ☆

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ABSTRACT

This study considers the problem of determining the locations of collection points as well as the allocations of refuses at demand points to collection points while satisfying the capacity and the maximum allowable collection distance constraints at each collection point. To consider fluctuating demands commonly occurred in refuse collection systems, we consider a restricted dynamic version of the problem in which the locations are fixed, but the allocations are changed over a given planning horizon. The problem is formulated as an integer programming model for the objective of minimizing the sum of fixed costs to open collection points and variable costs to transport refuses between demand and collection points, and then, due to the complexity of the problem, two heuristic algorithms are suggested. The heuristics, called the multi-stage branch and bound and the modified drop heuristics in this paper, are based on the decomposition of the entire problem into the static location and the dynamic allocation sub-problems. Computational experiments were done on various test instances, and the results are reported.

1. Introduction

During the last decade, considerable attention has been paid to the emerging concept of reverse logistics due to environmental concerns such as natural resource depletion, pollutant emissions and biodiversity. Reverse logistics, the opposite direction of the conventional forward logistics, is defined as the logistics activities that end-of-use/life products or wastes no longer required by users are delivered to facilities for further product recovery or environmentally conscious disposal (Fleischmann et al., 1997). In other words, it is related with the reversed domain from customers to collectors, re-processors, recyclers, and disposers, compared to the forward logistics from suppliers to customers.

One of indispensable reverse logistics activities is refuse collection that gathers end-of-use/life products or wastes and moves them to the facilities where further recovery or disposal is done. Here, end-of-use/life products or wastes are called refuses in solid waste management (Vesilind, Worell, & Reinhart, 2002). In general, a refuse collection system consists of collection points, recovery and disposal facilities, workers, etc. Here, collection points, i.e. places where refuses are gathered and handled for further treatments, are important structural elements in designing and operating refuse collection systems.

There are various decision problems in refuse collection (Dowlatshahi, 2000; Fleischmann, Krikke, Dekker, & Flapper, 2000; Lee, Kim, & Kim, 2008; Mansini & Speranza, 1998; Sasikumar & Kannan, 2008; Srivastava, 2007). Among them, this study focuses on the network design problem. More specifically, the problem is to determine the locations of collection points as well as the allocations of refuses at demand points to collection points while satisfying the relevant constraints. In particular, we consider a restricted dynamic version of the problem, i.e. the locations of collection points are fixed (static locations), but the allocations are changed over a planning horizon (dynamic allocations), so that the fluctuating refuse demands can be explicitly considered.

The previous studies on reverse logistics network design can be classified into static and dynamic ones. For literature reviews on various network design problems in reverse logistics, see Srivastava (2007), Lee et al. (2008), Akçali, Çetinkaya, and Üster (2009), Melo, Nickel, and Saldanha-da-Gama (2009), and Ilgin and Gupta (2010).

Most previous studies on refuse collection network design are static ones, i.e. single-period models using aggregated refuse demands for a certain period of time. Bautista and Pereira (2006) report a case study on the problem of determining the locations of collection areas in an urban waste management system of the metropolitan area in Barcelona, and Wojanowski, Verter, and Boycai (2007) suggest an analytical model that determines the locations of identical retail-collection facilities as well as the sales price to maximize the expected profit. Aras and Aksen (2008) provide a mixed integer nonlinear programming model to determine

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the locations of collection centers as well as the incentive values for each return type so as to maximize the profit obtained from the returns. Also, Kim and Lee (2008) and Kim, Choi, and Lee (2010) suggest heuristic algorithms for the static problem of determining the locations of collection points and the allocation of refuses at demand points to collection points under the capacity restriction at each collection point.

Some previous studies consider dynamic network design, especially for the entire reverse logistics or the integrated forward/reverse logistics networks. Pugh (1993) suggests a mathematical model for dynamic allocation of waste flows from a source to a given set of treatment and disposal facilities under the capacity constraint over a planning horizon. Ko and Evans (2007) suggest a genetic algorithm based heuristic for the multi-period capacitated network design problem in integrated forward and reverse logistics networks. The main decisions are the amounts of forward and reverse flows in each period and the dynamic locations and capacities of warehouses and repair centers in each period. Later, Min and Ko (2008) suggest another heuristic for the earlier problem additionally with consolidation/transshipment facilities and warehouses. Mansour and Zarei (2008) develop a multiple start search algorithm for the multi-period reverse logistics network design model that determines the numbers and locations of collection centers and dismantlers, together with their capacities, as well as the amounts of material flows among facilities in each period. Recently, El-Sayed, Afia, and El-Kharbotly (2010) suggested a stochastic mixed integer linear programming model for a multi-period forward and reverse logistics network design problem with three echelons (suppliers, facilities and distribution centers) in forward direction and two echelons (disassembly and redistribution centers) in reverse direction. Unlike these, to the best of the authors' knowledge, there is no previous study on the dynamic version of the refuse collection network design problem.

As stated earlier, we consider a restricted dynamic collection network design problem (RD-CNDP) that determines the static locations of collection points as well as the dynamic allocations of refuses at demand points to collection points over a given planning horizon, while satisfying the capacity and the maximum allowable collection distance constraints at each collection point. Here, the capacity constraint implies that there is an upper limit on the amount of collection at each collection point, and the maximum allowable collection distance constraint implies the refuses at demand points can be allocated to the collection point within an allowable distance.

Compared with the previous studies, the RD-CNDP has several features observed from a real municipal refuse collection system in Korea. First, the system scope is narrowed to the collection network, not the entire reverse logistics network, and hence we provide a more concrete and applicable model that can be used as a basic building block for designing the entire reverse logistics network. Note that the previous dynamic models are too simple to consider the detailed characteristics of reverse logistics. Second, the RD-CNDP considers the dynamic refuse demands explicitly in such a way that the collection points are remained fixed while allocations are done dynamically over a planning horizon. This is because it is highly unlikely to change collection points due to large fixed costs to open or close them and larger total costs due to frequent changes in the locations of collection points. Note that the previous single-period models make the two decisions, locations and allocations, statically using aggregate demands over a planning horizon. Finally, the RD-CNDP incorporates the maximum allowable collection distance, i.e. physical distance limit between collection and demand points. This is practical because it is unlikely that customers gather their refuses to a farther collection point. Also, it can prevent collection points to be located closely since one may obtain impractical solutions in which collection points are located too closely without the distance constraint.

To represent the problem mathematically, the RD-CNDP is formulated as an integer programming model. Then, due to the problem complexity, two heuristic algorithms, the multi-stage branch and bound and the modified drop heuristics, are suggested in this study. Each of the heuristics is based on the decomposition of the entire problem into the static location and the dynamic allocation sub-problems. Computational experiments were done on various test instances, and the results are reported.

This paper is organized as follows. In the next section, the problem is described in more detail with an integer programming model and the assumptions required. The two heuristics and their test results are presented in Sections 3 and 4, respectively. Finally, Section 5 concludes the paper with a summary and provides some areas for further research.

2. Problem description

This section explains the problem considered in this study, together with the assumptions required. An integer programming model is also provided to represent the problem more clearly, and then its problem complexity is briefly shown.

The RD-CNDP can be briefly described as follows: *for a given set of potential sites, the problem is to determine the static locations of collection points and the dynamic allocations of demand points to the opened collection points for the objective of minimizing the sum of fixed and variable costs over a given planning horizon with discrete time periods, while satisfying the capacity and the maximum allowable collection distance constraints*. It is assumed that the potential sites are given in advance. Note that a potential site is used as a synonym of a demand point in this paper, and hence refuse demands occur at potential sites. It is assumed that the amount of refuse (or demand) at each demand point in each period is deterministic and given in advance.

The RD-CNDP has two main decisions: location and allocation. The location is done by opening collection points among the potential sites. As stated earlier, the collection points are fixed and remained unchanged over the planning horizon, i.e. static locations. Also, the allocation decision is done by assigning demand points to opened collection points in each period of the planning horizon, i.e. dynamic allocations. It is assumed that each demand point is allocated to exactly one collection point, i.e. no demand splitting is allowed.

As in other network design problems, the fixed and variable costs in the objective function are associated with opening collection points and transporting refuses, respectively. The fixed costs, which may be different at collection points, are assumed to be given and deterministic, and the variable costs, which are directly proportional to the distances and the amounts of refuse, are also assumed to be given and deterministic. Also, it is assumed that the fixed and the variable costs remain fixed over the planning horizon.

As explained earlier, the RD-CNDP considered in this study has two main constraints: (a) capacity restrictions; and (b) maximum allowable collection distances. First, the capacity restriction at each collection point implies that there is an upper limit on the amounts of refuses at demand points when they are allocated to the collection point. For example, the Korean municipal refuse collection system uses various collection buckets, i.e. 1, 2.5, 4.5, 5, 8, 11, and 13.5 tons, at collection points. Second, the maximum allowable collection distance at each collection point implies that no demand points beyond its distance limit can be allocated to the collection point. It is assumed that the capacity and the maximum allowable collection distance at each potential site are assumed to be deterministic and given in advance. Note that we consider a generalized version of the problem in which the capacities and the maximum allowable collection distances may be different at collection points.