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Dynamic network design for reverse logistics operations under uncertainty

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ABSTRACT

The design of reverse logistics network has attracted growing attention with the stringent pressures from environmental and social requirements. In general, decisions about reverse logistics network configurations are made on a long-term basis and factors influencing such reverse logistics network design may also vary over time. This paper proposes dynamic location and allocation models to cope with such issues. A two-stage stochastic programming model is further developed by which a deterministic model for multiperiod reverse logistics network design can be extended to account for the uncertainties. A solution approach integrating a recently proposed sampling method with a heuristic algorithm is also proposed in this research. A numerical experiment is presented to demonstrate the significance of the developed stochastic model as well as the efficiency of the proposed solution method.

1. Introduction

Logistics network design problems that take into account the facility locations and the shipment of the product flows have been extensively tackled for decades. Recently, due to the increasing stringent pressures from environmental and social requirements, more and more manufacturers have adopted the practice of using returned products and incorporated product recovery activities into the production. Consequently, the design of reverse logistics network is gaining concern, which concerns not only the economic aspects but also how logistics network will affect other aspects of human life, such as the environment and sustainability of natural resources. Implementation of the reverse logistics operations requires setting up additional appropriate logistics infrastructure for the arising flows of used and recovered products. Physical location, facilities and transportation links need to be chosen to transfer forward products from manufacturers to customers and to convey used products from their former users to manufacturers for the purpose of recovery or safe disposal. Furthermore, the interaction between the distribution of forward products and returned products also needs to be considered due to the influence of the activities of reverse logistics on forward logistics such as the occupancy of the storage spaces and transportation capacity.

In practice, decisions about reverse logistics network configurations are made on a long-term basis. Depots, distribution centers and transshipment points once established shall be used for a couple of periods. Van Roy and Erlenkotter (1982) described the dynamic simple plant location problem without capacity constraints, considering that a facility can be open at the beginning of a time period. If there are open facilities at the beginning of the planning horizon, these existing facilities can be closed at the end of a time period. They also proposed a branch-and-bound algorithm that uses a dual ascent procedure and presented computational results to show the efficiency of the method. Realff et al. (1999) analyzed the network performance in a dynamic environment. Facility locations and capacities must be fixed for the entire planning horizon in

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their models. Hinojosa et al. (2000) dealt with the problem of multiproduct dynamic location and developed a heuristic procedure based on a Lagrangean relaxation. Antunes and Peeters (2001) presented a dynamic location problem that considers the location of new facilities, or the closure, reduction or expansion of the existing facilities. They also provided a study on the advantages and limitations of simulated annealing to solve this problem. Recently, Dias et al. (2007) developed a dynamic location model considering the possibility of reconfiguring any location more than once over the planning horizon. They also proposed a primal–dual heuristic to obtain the solution.

However, all the aforementioned researches assumed that the operational characteristics of, and hence the design parameters for, the logistics network were deterministic. Generally, the characteristics of reverse logistics network may include considerable system uncertainty. Both markets for forward products and supply of used products by customers typically involve many unknowns. Fleischmann et al. (2000) also pointed out that uncertainty is an important characteristic of product recovery, so this issue seems to deserve additional research effort. More comprehensive quantitative results would be useful, concerning the impact of uncertainty on recovery network design and the appropriateness of traditional approaches for capturing this element. In order to handle the problem with such stochastic aspects, Liste and Dekker (2005) proposed a stochastic programming approach by which a deterministic location model for product recovery network design was extended to account for the uncertainties. However, this research for network design under uncertainty can only address a modest number of scenarios for the uncertain problem parameters. Salema et al. (2007) proposed a generalized model for the design of reverse logistics networks. The model is based on the recovery network model proposed by Fleischmann et al. (2001). They developed a capacitated multi-product reverse logistics network model with uncertainty. The capacity constraints are imposed on the total production/storage capacity of the facilities, which may be factories, warehouses or distribution centers. However, it is also mentioned that as the problem size increases, the computational burden might be expected to grow accordingly. Hence, to deal with such stochastic large-scale network design problem, Santoso et al. (2005) applied a recently proposed sampling strategy, which is based on crude Monte Carlo samples. But the major disadvantage of such a sampling approach is that some computational effort might be wasted on optimizing when the approximation is not accurate. Moreover, none of the aforementioned researches considered the dynamic aspect in an uncertain reverse logistics network context.

Therefore, this paper proposes dynamic location and allocation models with stochastic parameter settings to cope with such issues. A stochastic programming model is developed by which a deterministic model for dynamic reverse logistics network design can be extended to explicitly account for the uncertainties. Since almost all the existing approaches for solving these problems are either restricted to deterministic situations or can only deal with a modest number of scenarios for the uncertain problem parameters, a solution approach integrating a sample average approximation (SAA) method with a simulated annealing (SA) algorithm is developed. A numerical experiment is also presented to demonstrate the significance of the developed stochastic model as well as the efficiency of the proposed solution approach.

2. Model development

The general structure of a dynamic reverse logistics network is illustrated in Fig. 1. Heterogeneous forward products are delivered to a number of geographically dispersed customers from plants via forward processing facilities. Returned products are taken back from the customers and shipped to the plants via return processing facilities for the purpose of recovery or safe disposal. In this paper, instead of only handling separate forward processing and collection facilities, a new type of intermediate depots, namely hybrid processing facility, is also taken into account. Both forward products and returned products can be transferred via hybrid processing facilities. Advantages of building such hybrid processing facilities might include cost savings and pollution reduction as a result of sharing material handling equipment and infrastructure. In a dynamic version of the attempted network design, for every facility a close or open option is available at the beginning of every period $t = 1, \ldots, T$, where T denotes a given planning horizon. The cost associated with such relocation of facilities is taken into account.

2.1. Deterministic programming model

A deterministic mixed integer nonlinear programming (MINLP) model is first proposed for the attempted problem. The following notations are used in the model formulation.

Indices used in the model: $I = \{1, \ldots, i\}$ set of plants
$J = \{1, \ldots, j\}$ set of potential depots
$K = \{1, \ldots, k\}$ set of customers
$N = I \cup J \cup K$ set of nodes in the network
$P = \{1, \ldots, p\}$ set of product types
$T = \{1, \ldots, t\}$ set of time periods in a given planning horizon

Parameters of the model:

d_{kp}^t demand of forward product p at customer k during time period t $\forall k \in K,\ p \in P,\ t \in T$
s_{kp}^t supply of returned product p at customer k during time period t $\forall k \in K,\ p \in P,\ t \in T$