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The design of sustainable logistics network under uncertainty

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A R T I C L E I N F O

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A B S T R A C T

The design of sustainable logistics network has attracted growing attention with the stringent pressures from environmental and social requirements. This paper proposes a stochastic programming based approach to account for the design of sustainable logistics network under uncertainty. A solution approach integrating the sample average approximation scheme with an importance sampling strategy is developed. A case study involving a large-scale sustainable logistics network in Asia Pacific region is presented to demonstrate the significance of the developed stochastic model and the efficiency of the proposed solution approach.

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 increase in 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, a focus on logistics network design is a step towards the broader adoption and development of sustainability, 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. Sustainability stretches the concept of logistics network design to look at optimizing operations from a broader perspective—the entire production system and postproduction stewardship as opposed to just the production of a specific product (Linton et al., 2007). Implementation of sustainable logistics operations requires setting up additional appropriate logistics infrastructure for the arising flows of used and recovered products, which adds an additional level of complexity to traditional logistics network design. 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. Thus, the network design issues in the sustainable logistics system involve two categories with respect to the material flows: forward product flow and returned product flow.

For the traditional forward logistics environments, a number of standard mixed integer linear programming (MILP) approaches have been developed that are commonly recognized (Mirchandani and Francis, 1989). For the reverse logistics context, a standard set of model has not yet been established. Spengler et al. (1997) developed an MILP model for recycling of industrial byproducts. The model was based on the multi-level capacitated facility location problem modified for the special problem structure. Jayaraman et al. (1999) analyzed the logistics network of an electronic equipment remanufacturing company in the USA. A single period MILP model based on a multi-product capacitated warehouse location model was developed. Shih (2001) proposed a new MILP model to optimize the infrastructure design and the reverse network flow for the recovery of electrical appliances and computers.

As summarized from the aforementioned discussion, most studies of the existing network models only consider a single flow such as forward or reverse flow, whereas the activities of reverse logistics may have strong influence on the operations of forward logistics such as the occupancy of the storage spaces and transportation capacity. Fleischmann et al. (2001) developed an MILP model to analyze the impact of product recovery on sustainable logistics network design. Ko and Park (2005) also proposed an MILP model to illustrate the impact of an integrated solution on the sustainable logistics network design. However, both the aforementioned research assumed that the operational characteristics of, and hence the design parameters for, the sustainable logistics network were deterministic. In practice, the characteristics of sustainable logistics network include considerable system uncertainty. Both markets for forward products and supply of used products by customers typically involve many unknowns (Corbett and Klassen, 2006). For the studies of logistics network planning problem under uncertainty, Li et al. (2009) developed a hybrid simulation optimization method for production planning of dedicated remanufacturing under uncertainty. Rastogi et al. (2010) studied the supply network capacity planning

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for semiconductor manufacturing by considering the uncertainty of the future demand. In this paper, a two-stage stochastic programming model is proposed to explicitly account for the design of sustainable logistics network under uncertainty. A solution approach integrating the sample average approximation scheme with an importance sampling strategy is developed to solve a case study with a large number of scenarios.

2. Sustainable logistics network model

The general structure of a sustainable logistics network is illustrated in Fig. 1. Heterogeneous forward products are delivered to a number of geographically dispersed customers from manufacturers via forward processing facilities. Returned products are taken back from the customers and shipped to the manufacturers via collection 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. Thus, advantages of building such facilities might include cost savings and pollution reduction as a result of sharing material handling equipment and infrastructure (Jayaraman et al., 1999).

2.1. Deterministic programming model

A deterministic mixed integer linear programming model is firstly 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 manufacturers;
$J=\{1,\ldots,j\}$ 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 products.

Parameters of the model:

d_k^p	demand of forward product p at customer k, $\forall k\in K$, $p\in P$;
s_k^p	supply of returned product p at customer k, $\forall k\in K$, $p\in P$;
u_j^p	capacity for handling forward product p at depot j if forward processing facility is built at depot j, $\forall j\in J$, $p\in P$;
l_j^p	capacity for handling forward product p at depot j if hybrid processing facility is built at depot j, $\forall j\in J$, $p\in P$;
v_j^p	capacity for handling returned product p at depot j if collection facility is built at depot j, $\forall j\in J$, $p\in P$;
m_j^p	capacity for handling returned product p at depot j if hybrid processing facility is built at depot j, $\forall j\in J$, $p\in P$;
c_{ijk}^p	shipping cost per unit of forward product k shipped from manufacturer i to customer k via depot j, $\forall i\in I$, $j\in J$, $k\in K$, $p\in P$;
e_{kji}^p	shipping cost per unit of returned product k shipped from customer k to manufacturer i to via depot j, $\forall k\in K$, $j\in J$, $i\in I$, $p\in P$;
f_j	fixed cost of building forward processing facility at depot j, $\forall j\in J$;
r_j	fixed cost of building collection facility at depot j, $\forall j\in J$;
h_j	fixed cost of building hybrid processing facility at depot j, $\forall j\in J$;
n_j^p	processing cost per unit of forward product p at depot j, $\forall j\in J$, $p\in P$;
t_j^p	processing cost per unit of returned product p at depot j, $\forall j\in J$, $p\in P$.

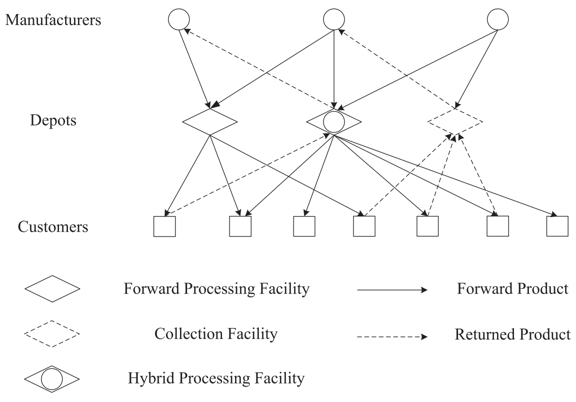

Fig. 1. A depiction of the sustainable logistics network structure.

The decisions of the sustainable logistics network configuration consist of deciding the type of facility to build at each potential depot, the quantities of forward and returned products shipped in the transportation links. The decision variables of the model are as follows:

$$x_j=\begin{cases}1 & \text{if forward processing facility is built at depot } j, \forall j\in J;\\ 0 & \text{otherwise;}\end{cases}$$

$$y_j=\begin{cases}1 & \text{if collection facility is built at depot } j, \forall j\in J;\\ 0 & \text{otherwise;}\end{cases}$$

$$z_j=\begin{cases}1 & \text{if hybrid processing facility is built at depot } j, \forall j\in J;\\ 0 & \text{otherwise;}\end{cases}$$

q_{ijk}^p	quantity of forward product p shipped from manufacturer i to customer k via depot j, $\forall i\in I$, $j\in J$, $k\in K$, $p\in P$;
g_{kji}^p	quantity of returned product p shipped from customer k to manufacturer i via depot j, $\forall k\in K$, $j\in J$, $i\in I$, $p\in P$.

The objective function is formulated in the following equation:

$$\text{(F)}\ \min\sum_{j\in J}f_jx_j+\sum_{j\in J}r_jy_j+\sum_{j\in J}h_jz_j+\sum_{i\in I}\sum_{j\in J}\sum_{k\in K}\sum_{p\in P}(c_{ijk}^p+n_j^p)q_{ijk}^p+\sum_{k\in K}\sum_{j\in J}\sum_{i\in I}\sum_{p\in P}(e_{kji}^p+t_j^p)g_{kji}^p \tag{1}$$

subject to

$$\sum_{i\in I}\sum_{j\in J}q_{ijk}^p\geq d_k^p\quad \forall k\in K,\quad p\in P \tag{2}$$

$$\sum_{i\in I}\sum_{k\in K}q_{ijk}^p\leq u_j^px_j+l_j^pz_j\quad \forall j\in J,\quad p\in P \tag{3}$$

$$\sum_{j\in J}\sum_{i\in I}g_{kji}^p\geq s_k^p\quad \forall k\in K,\quad p\in P \tag{4}$$

$$\sum_{k\in K}\sum_{i\in I}g_{kji}^p\leq v_j^py_j+m_j^pz_j\quad \forall j\in J,\quad p\in P \tag{5}$$

$$x_j+y_j+z_j\leq 1\quad \forall j\in J \tag{6}$$

$$q_{ijk}^p\geq 0\quad \forall i\in I,\quad j\in J,\quad k\in K,\quad p\in P \tag{7}$$

$$g_{kji}^p\geq 0\quad \forall k\in K,\quad j\in J,\quad i\in I,\quad p\in P \tag{8}$$

$$x_j\in\{0,1\}\quad \forall j\in J \tag{9}$$