A DYNAMIC MODEL FOR THE DESIGN OF GREEN LOGISTIC NETWORKS

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Abstract

The application of green concepts for supply chain management represents a new fundamental way for companies to reach competitiveness, not only in terms of efficiency but also in terms of added value creation for the final customer. In particular, reverse logistics aims at optimizing reverse product flows to limit residual waste. One of the most critical problems in the reverse logistics field is the design of green logistic networks. The purpose of this work is therefore to propose a comprehensive generic model which can help decision makers to design such networks that cover remanufacturing activities. This model could also help devising strategies for the pricing of used and remanufactured products.

Keywords: Reverse logistics, Green supply chain design, Optimization.

1. Introduction

Reuse of products and materials is not a new phenomenon. In all cases the reuse opportunities give rise to a new material flow from the end user back to the producers. The management of this material flow is the concern of the new field of “reverse logistics”. Reverse logistics refers to all activities dedicated to the treatment of return-products until they are properly recovered or disposed of within supply chains. These activities are supported by specific facilities which can be of two different main types, see Melo and Saldanha-da-Gama (2009): collection centres (i.e., facilities where customers hand in used products) and rework sites (remanufacturing centres and repair and refurbishing centres). In this context, the network structure needs to be extended with transportation links for return flows from customer locations to sites where repair, remanufacturing and/or recycling activities take place.

The aim of this work is therefore to propose a generic and comprehensive model for the green design of reverse supply chains that cover remanufacturing activities. One special characteristic to be taken into account when designing reverse chains is the high degree of uncertainty in the supply of used products returned by the consumers both in terms of quantity and quality. Moreover, products may be returned during their life cycle (commercial returns, warranties, repairs), at the end of use, or at end of life requiring to consider the characteristics of the returned products to optimize the value-recovery process. These are the features which are overlooked in the literature and are included in this work, see Melo and Saldanha-da-Gama (2009). More precisely the model is dynamic considering seasonality and uncertainty of product returns at the end of use. Moreover, multiple classes of products may be collected and treated in a same period of time to optimize transportation and ensure continuous functioning of remanufacturing centres.

Another particularity of reverse chains is that end-markets for recovered products may not be well known, see Fleischmann et al. (1997). In addition to that, required skills and expertise may differ and thus impose constraints on the potential actors involved in reuse activities which can be either the original producer or a third party, see Min and Ko (2008). These different actors take part of the reverse logistic network considered in this work.

The last originality of this work is the consideration of the environment when computing transportation costs. These latter are detailed in the remaining of the paper.
This work is organized as follows. First, the problem is described. Then, the mathematical model is presented. Computational results are presented in section 4. The last section concludes the paper and provides some directions for future research.

2. Model formulation

2.1 Presentation of the problem

In this section, the problem is presented. Figure 1 describes the network. The dynamic flow of multiple classes of product with stochastic returns is considered. The reverse supply chain consists in three main layers composed of collection points (which can be either customers or retailers), collection centres and remanufacturing centres. More precisely, the products at the end of their life cycle are taken back from collection points to collection centres. Then, if the returned products meet quality standards despite of their obsolescence, they can be sold in a secondary market. Otherwise, the products are treated in a remanufacturing centre or taken back by a subcontractor, depending on the available capacity at remanufacturing facilities. The lack of capacity obliges also big quantities of products to go to disposal sites. The purpose of the model is therefore to optimize the network and the reverse flow of products in a way that minimizes the quantity of products which are disposed off.

![Figure 1: Model diagram illustrating the problem](image)

The model consists of a dynamic two stage capacitated facility location problem (Sahin and Süral, 2007) which is solved in a sequential manner in order to better reflect real return flows. The planning horizon consists of a set of different periods corresponding to seasons. In a first phase, the problem of collecting uncertain quantities of product from collection points is formulated as an allocation-location model. Then, when the available quantity of each class of products is known at each collection center, a p-median problem is addressed in order to locate remanufacturing centers. Note that the facilities to locate are colored in green in the diagram.

Some assumptions have been made in order to better fit realistic network such as capacity constraints for the collection centres and for the remanufacturing centres to be set up. Moreover, the investment costs are supposed to be shared by the different stakeholders involved in the reverse chain (the authorities and the original manufacturer). These investments can be achieved step by step during the planning horizon since the costs for opening any centre are high. The possibility of including tax incentives for the recovery processes or subsidies from the local authorities as well as penalty costs for the products which are disposed off is also considered in this work.

The sets and indexes used in the model are as follows:

2.2 Indexes and sets
The parameters, variables and formulation of the problem are presented in what follows.

2.3 Model parameters, decision variables and first level allocation-location formulation

The parameters of the problem are the following:

- $FS_j$ = fixed cost of setting up a collection centre at site $j$,
- $FO_j$ = fixed costs for operating collection centre $j$,
- $d_{ij}$ = distance between collection point $i$ and collection centre $j$ in km,
- $c_{ij,v}$ = transportation costs per unit of weight from collection point $i$ to collection centre $j$ by vehicle $v$ in €/ton.km. These costs include the fixed costs for operating vehicle $v$ and the variable costs per kilometer, the variable costs per kilometer for the fuel consumption when empty, and the fuel consumption per ton.
- $M_{min}^j$ = minimum capacity of collection centre $j$,
- $M_{max}^j$ = maximum capacity of collection centre $j$,

In order to optimize the allocation of the collected products with regard to the capacity volume of each collection center, the size of each class of products is compared to a standard size.

- $S_p$ = average size of product $p$,
- $w_p$ = average weight of product $p$,
- $Q_{p,i,t}^t$ = available quantity of product $p$ collected at point $i$ during time period $t$,
- $Q_{max}^{p,i,t}$ = maximum quantity of product $p$ that can be collected at collection point $i$ for time period $t$,

The decision variables for the model are:

- $X_{j,t}$ = 1, if a collection centre is located and set up at potential site $j$ at time period $t$, 0, otherwise,
- $Y_{i,j,t}$ = 1, if collection point $i$ is assigned to collection centre $j$ at time period $t$, 0 otherwise,
- $V_{p,i,j,t} = \text{quantity of product } p \text{ shipped from collection point } i \text{ to collection centre } j \text{ during time period } t$.

The problem is to minimize quantity:

$$\sum_{t \in T} \sum_{j \in J} (FS_j + FO_j)X_{j,t} + \sum_{v \in V} \sum_{t \in T} \sum_{p \in P} \sum_{i \in I} c_{ij,v} w_p d_{ij} Y_{i,j,t} Q_{max}^{p,i,t}$$

Such that:

1. $\sum_{i \in I} Y_{i,j,t} = 1 \quad \forall j \in J, \forall t \in T$  
2. $Y_{i,j,t} \leq X_{j,t} \quad \forall i \in I, \forall j \in J, \forall t \in T$  
3. $\sum_{p} \sum_{i \in I} Q_{p,i,t} S_p Y_{i,j,t} \leq M_{max}^j X_{j,t} \quad \forall j \in J, \forall t \in T$  
4. $\sum_{p} \sum_{i \in I} Q_{p,i,t} S_p Y_{i,j,t} \geq M_{min}^j X_{j,t} \quad \forall j \in J, \forall t \in T$  
5. $\sum_{p} \sum_{i \in I} Y_{i,j,t} V_{p,i,j,t} \geq 0 \quad \forall j \in J, \forall i \in I, \forall p \in P, \forall t \in T$  
6. $X_{j,t}, Y_{i,j,t} \in \{0,1\} \quad \forall i \in I, \forall j \in J, \forall t \in T$
The objective function is divided into two parts: fixed costs for opening the facilities and operating them (which can be considered as an investment for a new site or for a new testing or sorting unit), and variable transportation costs related to the collection of the return products.

The first constraint ensures that each collection point is connected to only one collection center. Constraint (2) assigns collection point \( i \) to collection centre \( j \) in case it is opened. Constraints (3–4) are capacity constraints. The fifth set of constraints defines the real quantity of products shipped from collection point \( i \) to collection center \( j \) during time period \( t \). Constraints 6 check for non negativity and constraints (7) set binary conditions.

After the collection phase, the remanufacturing centers have to be located during the next phase. This corresponds to time period \( t+1 \).

2.4 Model parameters, decision variables and second level p-median formulation

\( d_{j\alpha} \) distance between collection centre \( j \) and point \( \alpha \), with \( \alpha \in \{k, l, m, n\} \)

\( c_{j\alpha} \) transportation costs per unit of weight from collection centre \( j \) to point \( \alpha \) by vehicle \( v \) in €/ton.km.

(note that these costs are calculated in a same manner as for the first level).

\( \gamma^{t+1} = 1 \) if a shipment is made from collection centre to subcontractors or disposal centre, \( 0 \) otherwise.

a. Parameters and decision variables linked to the secondary market

\( \beta^{t+1}_{p,j} \) percentage at which the checked return-products of class \( p \) in collection centre \( j \) will be sold at secondary market at time period \( t+1 \).

\( \text{dem}^{t+1}_{p,k} \) demand for class of product \( p \) at secondary market \( k \) at time period \( t+1 \).

\( U^{t+1}_{p,k} \) price of a product of class \( p \) at secondary market \( k \) at time period \( t+1 \).

\( V^{t+1}_{p,jk} \) quantity of product \( p \) shipped from collection centre \( j \) to secondary market \( k \) at time period \( t+1 \).

b. Parameters and decision variables linked to the remanufacturing centres

\( F_{S_l} \) fixed cost of opening a remanufacturing centre at potential site \( l \),

\( F_{ad}^{t+1} \) fixed adding costs corresponding to the capacity extension of remanufacturing centre \( l \) at \( t+1 \).

\( U^{t+1}_{p,l} \) Unitary benefit for a product of class \( p \) at remanufacturing centre \( l \) at time period \( t+1 \).

\( O^{t+1}_{p,l} \) Operational costs for the treatment of a product \( p \) at remanufacturing centre \( l \) at \( t+1 \).

In order to describe the processing capacity per product at remanufacturing centres, a workload is used. \( WL_{p,l}, WL_{\text{tot}l}, WL_{\text{tot}_{ad}l} \) represent respectively the workload to treat product \( p \), the total workload available, and the adding workload at remanufacturing centre \( l \).

\( V^{t+1}_{p,jl} \) volume of product \( p \) shipped from collection centre \( j \) to remanufacturing centre \( l \) during \( t+1 \).

\( nrc^{t+1} \) number of remanufacturing centres which should be opened at time period \( t+1 \)

\( X^{t+1} \) = 1, if a remanufacturing centre is located and set up at potential site \( l \) at time period \( t+1 \), 0, otherwise.

c. Parameters and decision variables linked to the subcontractors

\( U^{t+1}_{p,m} \) Unitary benefit for a product of class \( p \) at subcontractor \( m \) at time period \( t+1 \).

\( O^{t+1}_{p,m} \) Operational costs for the treatment of a product \( p \) at subcontractor \( m \) at time period \( t+1 \).

\( M^{t+1}_{p,m} \) Total capacity for products of class \( p \) at subcontractor \( m \) at time period \( t+1 \).

\( V^{t+1}_{p,jm} \) volume of product \( p \) shipped from collection centre \( j \) to subcontractor \( m \) at time period \( t+1 \).

d. Parameters and decision variables linked to the disposal centres
Pe_{t+1}^{p,n} = Unitary penalty cost for the elimination of a product of class p at disposal centre n at t+1. (This cost can represent the virgin matter that could not be recovered.)

O_{t+1}^{p,n} = Operational costs for the elimination of a product p at disposal centre n at time period t+1.

M_{p,n}^{t+1} = Total capacity for products of class p at disposal centre n during time period t+1.

V_{p,tn} = Volume of product p shipped from collection centre j to disposal centre n at time period t+1.

The p-median problem consists in minimizing

\[
\sum_{v \in V} \sum_{t \in T} \sum_{p \in P} \sum_{j \in J} \sum_{l \in L} (c_{jk}^t w_{pj}^j - U_{p,kj}^t) V_{pj,l}^t + \sum_{t \in T} \sum_{l \in L} (FS_t + F_{ad,l}^t) X_{l}^t
\]

\[+ \sum_{v \in V} \sum_{t \in T} \sum_{p \in P} \sum_{j \in J} \sum_{l \in L} (c_{jl}^t w_{pj}^j - U_{p,lj}^t + O_{p,lj}^t) V_{pj,l}^t\]

\[+ \sum_{v \in V} \sum_{t \in T} \sum_{p \in P} \sum_{j \in J} \sum_{l \in L} \sum_{m \in M} (c_{jm}^{p} w_{pj}^j - U_{p,mj}^{p} + O_{p,mj}^{p}) V_{pj,m}^{p}\]

\[+ \sum_{v \in V} \sum_{t \in T} \sum_{p \in P} \sum_{j \in J} \sum_{l \in L} \sum_{m \in M} \sum_{n \in N} (c_{jn}^{p} w_{pj}^j + Pe_{p,n}^{t+1} + O_{p,n}^{t+1}) V_{pj,n}^{t+1}\]

Such that:

\[\sum_{t \in T} X_{l}^t = nrc_{l}^{t+1}\]

\[\sum_{p \in P} V_{pj,l}^t = \sum_{j \in J} V_{pj,l}^t + \sum_{m \in M} V_{pj,m}^t + \sum_{n \in N} V_{pj,n}^t\]

\[\sum_{j \in J} V_{pj,l}^t \leq \beta_{p,j}^t \sum_{i \in I} V_{pi,l}^t\]

\[\sum_{j \in J} V_{pj,m}^t \leq \beta_{p,j}^t \sum_{i \in I} V_{pi,m}^t\]

\[\sum_{j \in J} \sum_{l \in L} W_{l} = (WL_{tot,ad} + WL_{tot,l}) X_{l}^t\]

\[\sum_{p \in P} \sum_{j \in J} V_{pj,m}^t \leq \gamma_{p,m}^t M_{p,m}^t\]

\[\sum_{p \in P} \sum_{j \in J} V_{pj,n}^t \leq \gamma_{p,n}^t M_{p,n}^t\]

\[V_{pj,l}^t \geq 0, \quad V_{pj,m}^t \geq 0, \quad V_{pj,n}^t \geq 0, \quad X_{l}^t \in \{0,1\}\]

\[\forall t \in T\]

\[\forall p \in P, \forall t \in T\]

\[\forall j \in J, \forall p \in P, \forall t \in T\]

\[\forall k \in K, \forall p \in P, \forall t \in T\]

\[\forall l \in L, \forall t \in T\]

\[\forall m \in M, \forall t \in T\]

\[\forall n \in N, \forall t \in T\]

\[\forall j \in J, \forall k \in K, \forall p \in P, \forall t \in T\]

\[\forall m \in M, \forall n \in N, \forall p \in P, \forall t \in T\]

\[\forall l \in L, \forall t \in T\]

3. Computational results

In order to evaluate the model, it is applied to realistic scenarios. LINGO 12 has been used to solve the programs and to obtain exact solutions by using Branch and Bound with default parameters of the solver. The number of time periods T is 12 to describe a total investment decomposed in three years. The locations of all facilities have been uniformly distributed in the square [0, 140] x [0, 140]. For each time period, the available quantities of the three classes of products to be collected from 15 collection points are generated randomly using a uniform distribution over different spaces. The authorized gross weights for the trucks are respectively 12 tons and 25 tons for the first and second level transportation. The fixed costs for opening the facilities are computed using the same method as in Thanh et al., (2008). The adding capacity for the remanufacturing centres is 25% at the end of each year. Using these definitions for data generation, several instances have been created for all problem types.

The results of the computations are summarized in figure 2. At the end of the planning horizon, six collection centres and three remanufacturing centres have been opened out of respectively eight and four possible locations.
Figure 2: Recovery rate per product during the planning horizon

Figure 2 shows the recovery rate for the three classes of products along the planning horizon. After one year and a half, more than 40% of the products can be recovered. The third year, the investments permit to remanufacture more than 60% of the products taken back from the consumer.

4. Conclusion and prospects

In this work, a dynamic model for the green design of reverse logistic networks has been proposed. To comply with the complexity of real industrial cases, characteristics such as the seasonality of product returns and the possibility of capacity expansions have been taken into account. Transportation costs have been computed by including environmental costs in terms of carbon dioxide emissions. Possible extensions of this work are the development of some heuristics and metaheuristics for greater size instances of this class of problem.

5. References


