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Supply-chain network configuration for product recovery

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Keywords Supply chain, remanufacturing, location model

Abstract. The current growth in consumption results in resource reduction, increasing waste production and, ultimately, environmental deterioration. Both government and consumer concerns regarding these issues have been driving reduction efforts in waste and natural resource-usage. These environmental issues, in addition to economic opportunities, result in the concept of product cycles that oppose the traditional 'one-way' economy. One approach is to create product recovery networks in which used products are collected, reprocessed and later redistributed to the customer. Product recovery networks differ from typical forward-only networks. Therefore, specific work considering their issues is necessary. In this work, we study a closed-loop supply chain in which manufacturers produce new products and remanufacture used products. The decisions to be made are: which warehouses and collection centres should be open, which warehouses should have sorting capabilities and how much material should be transported between each pair of sites. The multi-period integer programming model uses the present worth method to jointly analyse investment and operational costs. A sensitivity analysis of the model is performed, and conclusions are made regarding model behaviour and performance.

1. Introduction

Environmental degradation is a growing global problem. Increased consumption results in increased use of raw material and energy, which leads to the depletion of natural resources. Additionally, the waste produced has also increased considerably. This environmental degradation is considerable and not sustainable by the earth's ecosystem (Beamon 1999). Both government regulations and consumer concerns regarding these issues have been driving waste and natural resource-usage reduction efforts. These environmental issues, in addition to economic opportunities, result in the concept of

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product cycles that oppose the traditional 'one-way' economy (Gungor and Gupta 1999).

One approach is to create product recovery networks. Product recovery networks involve collection of used products from the customer back to the supply chain, reprocessing and future redistribution to the market. Collection decisions require the redesign of the network supply chain; specifically, the number and location of collection and recovery centres and warehouses. The problem addressed in this research is the design of such a supply chain. More specifically, the primary objective of this research is to assess the impact of recovery systems issues on location decisions by developing and analysing a location model for product recovery systems.

2. Literature review

Used products are recovered in a variety of ways. Thierry *et al.* (1995) present a categorization of product recovery options. All options imply collection, reprocessing and redistribution. The main difference is in the reprocessing activities. *Repair* is simply to return failed products to 'working order' by fixing or replacing broken parts. *Refurbishing* involves replacement of critical modules if needed. The quality and service life of refurbished products are still lower than the quality and service life of new products. *Remanufacturing* returns the product to 'as new' condition through product disassembly and rigorous inspection of all modules. Worn-out or out dated parts and modules are replaced and tested. Technological upgrades may also be included. Remanufacturing tends to be performed in-house by manufacturers, since specific product knowledge is required. *Cannibalization* consists of recovering only some parts from used products to be used in other products or components. *Recycling* requires product disassembly for material separation without conserving any product structures.

Product recovery requires some changes to the traditional forward network. One approach is to add reverse flow capabilities to an already existing forward network (sequential design). Another approach is to redesign the network including simultaneously forward and reverse flows (integral design). Fleischmann *et al.* (2001) analyse the two approaches.

Material recovery (Barros *et al.* 1998, Spengler *et al.* 1997, Louwers *et al.* 1999 and Realff *et al.* 1999) as well as parts or product recovery (Jayaraman *et al.* 1999, Krikke *et al.* 1999 and Kroon and Vrijens 1995) are studied in the literature. Typically, material recovery networks are open-loop while part or product recovery networks are closed-loop. In most of the available literature, the objective is to minimize the overall costs. Special attention should be given when jointly considering investment and operational costs due to their differences in magnitude and frequency. The literature differs in how both types of costs are taken into account. Both Spengler *et al.* (1997) and Krikke *et al.* (1999) use a scenarios approach (with different investment costs) in which the mathematical model includes only operational costs. On the other hand, Jayaraman *et al.* (1999) use a fixed cost per year that includes investment and maintenance costs without considering the time value of money. Some authors use annualized equivalent costs based on depreciating total capital costs over a fixed horizon length (Barros *et al.* 1998, Gottinger 1988, Louwers *et al.* 1999 and Realff *et al.* 1999). Although they consider the depreciation of the invested capital, they do not consider the real value of future operational costs.

3. Model

This section describes the specific problem and mathematical model. In product recovery networks, used products are collected from the customer and returned to the supply chain, inspected, reprocessed and redistributed into the market. The specific type of product recovery considered in this study is remanufacturing. The problem considered may arise, for example, in appliance remanufacturing appliances and other types of electronic products, where the manufacturer expertise is essential in order to bring the product back to 'as new' condition. A slightly different situation, but one with a similar structure, arises in rental operations (particularly internet-based). Rental companies rent an assortment of goods, from DVDs to re-usable pallets, where some 'remanufacturing' may be required before returning the product to the rental cycle.

3.1. *Problem description*

The problem addressed in this work is depicted in figure 1. The network is comprised of four

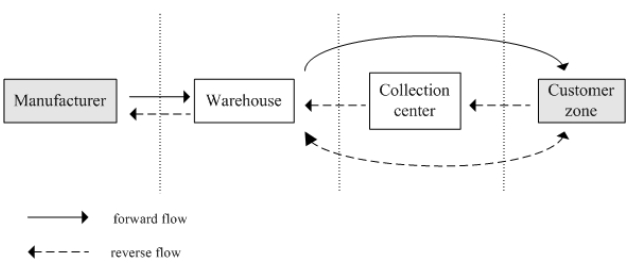

Figure 1. The product recovery network (with forward and reverse material flow).

echelons: manufacturers, warehouses, customer zones and collection centres. The details of this problem are given below:

- *Existing sites*. Manufacturers and customers are the existing sites in the network. Manufacturers, in addition to producing new products, receive used products to remanufacture. Customers are grouped in zones. Each customer zone has a known demand that must be satisfied. Moreover, customers return used products to the supply chain for remanufacture.
- *New facilities*. Warehouses and collection centres are the potential new facilities. Warehouses are used to store and distribute products from manufacturers to customer zones. Collection centres receive products returned by customers and send them back to manufacturers via warehouses. Each collection centre, in addition to the collection activity, is responsible for inspecting, testing and sorting the used products. For simplicity, the activity of inspection, testing and sorting will be subsequently referred to as *sorting*. Warehouses may also have sorting capabilities. This is required only if customers return used products directly to a warehouse (not through a collection centre).
- *Distribution*. Products (new and remanufactured) are transported from manufacturers to customers via warehouses, satisfying customer zone demand and incurring transportation costs. Holding costs are also incurred when products are stored in warehouses en route to customers.
- *Collection and recovery*. A certain amount of used products, defined as a percentage of demand, must be collected from each customer zone. Used products are transported to a collection centre or to a warehouse. Holding costs are incurred when used products are stored at these facilities. The sorting of products is based on their usability for reprocessing: products in good condition for remanufacture are *accepted*, the remainder are *rejected*. Accepted products are transported to warehouses, then back to manufacturers, and incur an associated transportation cost. Rejected products are disposed of or recycled (by other entities), outside the boundaries of the model.

The decision to be made is to determine from a finite number of possible locations (discrete problem) which warehouses and collection centres should be open in order to minimize the present loss (based on costs). This is a strategic-level problem. Therefore, all inputs, such as demands, availabilities, and costs, are considered to be known and outputs are specified as one-time decision values. Multiple periods are used uniquely for the purpose of considering the time value of money. Consequently, the problem is formulated as a deterministic, static, multi-period, mixed-integer linear program (MILP).

3.2. *Assumptions*

The following assumptions are used in the model.

- *Obligatory collection and recovery of used products*. An environmental motivation is assumed in this problem. Therefore, all returned products must be collected. Similarly, all collected products considered suitable for remanufacture must be recovered. All rejected products will be discarded.
- *Sorting and storage capacities*. Warehouses and collection centres are limited in sorting capacity (capacitated model). Storage capacity is assumed to be infinite. Therefore, for the purpose of this discussion, capacity refers to the sorting capacity.
- *Identical condition of new and recovered products*. Remanufacturing (the recovery option considered in this model) returns used products to 'as new' condition. Therefore, recovered products are assumed to be sold in the same condition as new ones to satisfy market demand.
- *Identical holding cost for new, used and tested products*. The model does not distinguish between the per-unit holding cost for forward products and used products. Used products may be slightly less valuable than new products. However, in remanufacturing, most of the value of the product is retained, thus the assumption of equal holding costs is minor. It is also assumed that used products have the same basic characteristics before and after sorting and therefore the same holding costs apply. The underlying assumption is that, although some disassembly may be performed during the sorting activities, the main disassembly is performed at the manufacturers.
- *Exclusion of production costs and remanufacturing costs*. Since collection and recovery is assumed obligatory, all returned products must be collected and all accepted products must be recovered. Therefore, the quantity of products to remanufacture is simply the number of accepted products (given), independent of the network design. Remanufacturing costs, based on the quantity of remanufactured products, are therefore fixed. Consequently, remanufacturing costs are excluded from the model. Similarly, since new and remanufactured products are assumed to be identical, the quantity of new products to produce is simply the difference between demand and the quantity of remanufactured products (both

given). Therefore, production costs, based on the quantity of new products, are fixed. Consequently, production costs are excluded from the model.

- *Exclusion of revenues*. Only costs are considered in the objective function. Revenues are based on sales of new and remanufactured products, mainly a function of volume. Therefore, revenues are assumed to be independent of the network design and are thus excluded.
- *Exclusion of disposal and recycling costs*. Since recovery is obligatory, only and all rejected products are to be discarded or recycled. The disposal and recycling costs incurred are dependent only on the quantity of rejected products and are therefore independent of the network design. Disposal and recycling sites are considered to be numerous and dispersed. Hence, the transportation costs incurred with disposal and recycling of rejected products are assumed to be independent of the location of the sites and are therefore not considered.

3.3. *Research contributions*

The model presented in this work considers both the forward flow (new and recovered products from manufacturers to customers) and the reverse flow (from customers back to the supply chain). Previous research has considered only the recovered products (excluding the new products) as forward flow. Since this research considers remanufacture only, new and used products are used to satisfy demand.

Some previous work proposes to pre-test and sort materials early in the supply chain in order to avoid transporting low-value material, which results in a decentralized network (Fleischmann *et al*. 1997, 2000), Realff *et al*. 1998). Therefore, the percentage of recoverable products (i.e., those in a suitable condition) is included in this work. The purpose of this is to test whether or not the condition of used products affects the network design.

Some previous research (Barros *et al*. 1998, Gottinger 1988, Louwers *et al*. 1999, and Realff *et al*. 1999), considers the depreciation of invested capital. However, they do not consider the real value of future operational costs. To improve the accuracy of the model (particularly in order to consider the investment and future operational costs) the 'present worth method' (PWM) is used. With this method, investment costs are considered once and per-cycle operational costs are considered over a horizon length (subject to an interest rate), in order to reflect the present equivalent of the future operational costs.

3.4. *Mathematical model*

The full mathematical formulation of the model is presented in Appendix A.

3.4.1. *Variables*

The primary objective of the model is to determine which of the potential facilities (warehouses and collection centres) will be open. Another objective of the model is to determine which warehouses should have sorting capability. The model also determines supply allocations – the quantities transported between pairs of sites (which define the allocation). Therefore, the following variables are defined:

$$x_w = \begin{cases} 1 & \text{if warehouse } w \text{ is open} \\ 0 & \text{otherwise} \end{cases}$$

$$y_c = \begin{cases} 1 & \text{if collection centre } c \text{ is open} \\ 0 & \text{otherwise} \end{cases}$$

$$s_w = \begin{cases} 1 & \text{if warehouse } w \text{ has sorting capability} \\ 0 & \text{otherwise} \end{cases}$$

$$q_{ij} = \text{quantity transported from site } i \text{ to site } j$$

3.4.2. *Parameters*

The following parameters are used in the model:

a_m = per-cycle quantity available from manufacturer m
b_{ij} = distance from i to j
c_w^i = cost of installing the sorting capability at warehouse w
c_w^{mw} = per-cycle cost of maintaining warehouse w
c_c^{mc} = per-cycle cost of maintaining collection centre c
c_w^{ow} = cost of opening warehouse w
c_c^{oc} = cost of opening collection centre c
c_w^s = per-cycle cost of sorting at warehouse w
c_{ij}^t = transportation cost per unit of product and per unit of distance from i to j
d_z = per-cycle customer zone z demand
g = percentage of used products in good condition for remanufacture
h_w^w = holding cost at warehouse w per unit of product per cycle
h_c^c = holding cost at collection centre c per unit of product per cycle
I = interest rate
k_w = sorting capacity at warehouse w
k_c = sorting capacity at collection centre c

r_z = percentage of demand returned by customer zone z
T = horizon length

3.4.3. *Objective function*

Operational costs are smaller per-cycle costs and therefore the time value of money should be considered (which makes operational costs non-linear). In order to jointly consider investment and operational costs a measure of investment worth is used. Among the several existing methods, PWM is selected (White *et al.* 1998). Since revenues are not considered (see assumptions), instead of maximizing present worth (with only negative terms, reflecting costs) the objective is to minimize *present loss*, PL. Present loss is defined as the investment costs plus the present equivalent of the future operational costs over a horizon length affected by an interest rate. The objective function is expressed in equation (1) of Appendix A. If depreciation is to be considered, the amount of the investment cost would be the accumulated depreciation over the planning horizon considered, rather than the total investment cost. The remaining value (total investment less the accumulated depreciation) is an estimate of the value of the investment that can be recovered by the end of the planning horizon, by sale or other disposition of the 'property' (White *et al.* 1998).

The costs considered in the objective function are expressed by equations (2) to (10) in Appendix A. *Opening cost* is an investment cost required to open a facility. *Installation cost* is an investment cost required to install sorting capability at a warehouse. Collection centres are assumed to always have sorting capabilities. Therefore, the installation cost at collection centres is included in the collection centre's opening cost parameter. *Maintenance cost* is the per-cycle cost required to maintain an open facility. Sorting cost is the per-cycle cost required to maintain the sorting activities in the warehouses in which they were installed. Collection centres are assumed to always have sorting capabilities. Therefore, the sorting cost at collection centres is included in the maintenance cost of collection centres. Products stored in facilities incur *holding costs*. *Transportation costs* to move materials between a pair of sites (i, j) are proportional to the distance travelled (b_{ij}) and the quantity transported (q_{ij}). In general, the transportation cost is expressed by the first term of equation (10) in Appendix A. However, the transportation cost of products returned from customers directly to warehouses is slightly different. This cost is affected by a penalty cost, depending on the percentage of used products considered to be in poor condition for remanufacture and subsequently sorted as rejected, $(1 - g)$. The objective here is to avoid the transportation costs incurred by transporting rejected products to warehouses. This should promote the existence of collection centres, proximal to customers, where used products can be inspected and rejected products can be sorted and disposed. In this case, the transportation cost is expressed by the second term of equation (10) in Appendix A.

3.4.4. *Constraints*

There are constraints on both the forward and the reverse flow of products. The flow constraints are: manufacturer's on-hand inventory, conservation of forward flow at warehouses, customer zone demand, customer zone returns, conservation of flow at collection centres, and conservation of reverse flow at warehouses. For *Flow constraints*, refer to equations (11) to (16) in Appendix A. Opening constraints are if–then constraints – if there are products leaving or arriving at a facility, then that facility must be open. For Opening constraints, refer to equations (17) to (20) in Appendix A. If a warehouse is not open, it cannot possess the capability of sorting used products. The *Installation constraints* in equation (21) in Appendix A guarantees that this capability be assigned only to open warehouses. All products must be sorted before being returned to the manufacturer. Therefore, a warehouse may only receive used products directly from customers if the warehouse has sorting capabilities. All collection centres have the capability of sorting. Thus, sorting constraints are not required for collection centres. For *Sorting constraints*, refer to equation (22) in Appendix A. Facilities (warehouses and collection centres) may not sort more than their sorting capacity. Only the products returned from customers directly to warehouses must be sorted at these facilities. At collection centres, all products returned by customers are tested and sorted. For *Capacity constraints*, refer to equations (23) and (24) in Appendix A.

4. Experimentation and analysis

Data were generated for the purpose of experimentation and analysis. In order to avoid making biased conclusions dependent on generated data multiple scenarios are created. Conclusions are therefore drawn for each scenario. This also allows identification of general tendencies, common to all scenarios. Different scenarios reflect different cost structures. Clearly, investment costs are higher than operational costs. Likewise, we assume that opening costs are higher than installation costs. Therefore, the attention focuses on operational costs. Operational costs (transportation costs, holding

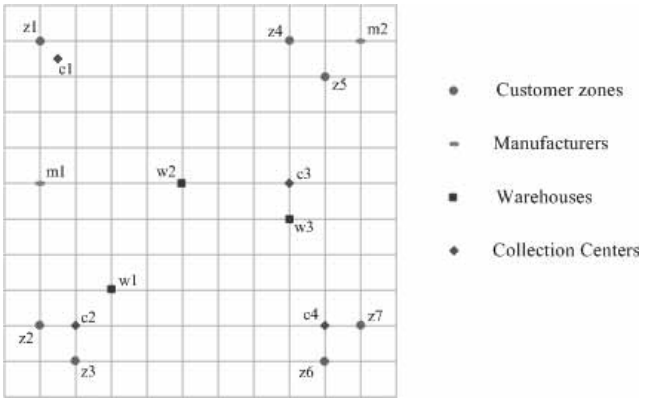

Figure 2. Location of existing and potential new facilities.

costs, maintenance costs and sorting costs) can vary widely relative to each other, depending on the type of business/product. For example, extremely valuable products may incur very high holding costs (compared to other operational components) while for products with special transportation requirements, transportation cost might be the major component. Therefore, to allow analysis of the effects of relative operational costs on network design, we create four scenarios which we will call problem types. Each problem type assumes that one component of the operational cost is higher than the other three. The four problem types are:

- Problem type *Maint* – maintenance cost is the highest component of the operational cost.
- Problem type *ITS* – inspection/testing/sorting cost is the highest component of the operational cost.
- Problem type *Trans* – transportation cost is the highest component of the operational cost.
- Problem type *Hold* – holding cost is the highest component of the operational cost.

An example problem was developed for the purposes of experimentation and analysis. This problem includes two manufacturers and seven customer zones. The potential new facilities are three warehouses and four collection centres. Figure 2 represents the location of existing sites and potential new facilities. The data used for the example problem are given in Appendix B.

4.1. *Results and analysis*

The primary purpose of our analysis is to study the sensitivity of the model to the relative values of the data. With this study we can at least conclude 'face validity' (the model appears to be acting appropriately under different situations). We were interested in knowing the effects of certain parameters on the design and costs. Therefore, for each of the four problem types, a sensitivity analysis was carried out on the following parameters: percentage of used products in good condition, g; horizon length, T; interest rate, I; investment costs, c_w^{ow}, c_c^{oc} and c_w^i; demand, d_z; percentage of demand returned, r_z; and transportation cost from customer zones to collection centres, c_{zc}^t .

The following format is used to represent the solution design: wi – to open warehouse i without sorting capability; si – to open warehouse i with sorting capability; ci – to open collection centre i. For example, {w1 c3} represents the solution design in which warehouse one without sorting capabilities and collection centre three are open. Results are shown by problem type. Results with the same solution design are grouped in blocks. A column with many blocks suggests that its problem type is very sensitive to the parameter being considered, while a column with few blocks indicates a problem type with a low sensitivity to the parameter being considered. Also, a block that spans several columns suggests similar behaviour across problem types, while different columns with different block patterns indicate that the problem types behave differently to variations in the same parameter.

4.1.1. *Results of model sensitivity to input parameters*

The condition of used products can vary widely. Different settings, such as different product types and different customer zones, may result in different condition of used products. Assuming a limited range would exclude some of these cases. Therefore, for parameter g, *Percentage of used products in good condition*, the model is tested across the entire range from 0% to 100%. The results are shown in table 1. The model is tested across a wide range of T, *Horizon length*, from one to 20 years. The results are shown in table 2. The *Interest rate*, I, is varied by increments of 1% from 0% to 20%. Results are presented in table 3. The model is tested within a

Table 1. Results for variations in parameter g.

Parameter	Problem type			
g	*Maint*	*ITS*	*Trans*	*Hold*
1	s1 c2 c4	s1 s3	s1 s3	s1 s3
0.9	s1 c2 c4	s1 c2 c4	s1 s3	s1 s3
0.8	s1 c2 c4	s1 c2 c4	s1 s3	s1 s3
0.7	s1 c2 c4	s1 c2 c4	s1 s3	s1 s3
0.6	s1 c3	s1 c3	s1 c3	s1 s3
0.5	s1 c3	s1 c3	s1 c3	s1 c3
0.4	s1 c3	s1 c3	s1 c3	s1 c3
0.3	s1 c3	s1 c3	s1 c3	s1 c3
0.2	s1 c3	s1 c3	s1 c3	s1 c3
0.1	s1 c3	s1 c3	s1 c3	s1 c3
0	s1 c3	s1 c3	s1 c3	s1 c3

Table 2. Results for variations in parameter T.

Parameter T	Problem type			
	Maint	*ITS*	*Trans*	*Hold*
1	s1 c2 c4	s1 c2 c4	s1 c2 c4	s1 c2 c4
...	s1 c2 c4	s1 c2 c4	s1 c2 c4	s1 c2 c4
9	s1 c2 c4	s1 c2 c4	s1 c2 c4	s1 c2 c4
10	s1 c2 c4	s1 c2 c4	s1 c2 c4	s1 s3
11	s1 c2 c4	s1 c2 c4	s1 c2 c4	s1 s3
12	s1 c2 c4	s1 c2 c4	s1 c2 c4	s1 s3
13	s1 c2 c4	s1 c2 c4	s1 s3	s1 s3
...	s1 c2 c4	s1 c2 c4	s1 s3	s1 s3
20	s1 c2 c4	s1 c2 c4	s1 s3	s1 s3

Table 3. Results for variations in parameter I.

Parameter I	Problem type			
	Maint	*ITS*	*Trans*	*Hold*
0	s1 c2 c4	s1 c2 c4	s1 c2 c4	s1 s3
0.04	s1 c2 c4	s1 c2 c4	s1 c2 c4	s1 s3
0.05	s1 c2 c4	s1 c2 c4	s1 s3	s1 s3
...	s1 c2 c4	s1 c2 c4	s1 s3	s1 s3
0.13	s1 c2 c4	s1 c2 c4	s1 s3	s1 s3
0.14	s1 c2 c4	s1 s3	s1 s3	s1 s3
...	s1 c2 c4	s1 s3	s1 s3	s1 s3
0.20	s1 c2 c4	s1 s3	s1 s3	s1 s3

wide range of values for parameter d_z, Demand, from 50% to +50% of the initial value. The results are shown in table 4. *Investment cost* is analysed across a wide range, from 50% to 200% of its initial value. The results are shown in table 5. Each customer may return none, part or all of the products received. Therefore, this parameter r_z, *Percentage of demand returned*, ranges from zero (0%) to one (100%). The results are shown in table 6. In some cases, the *Transportation cost per unit of product from customer zones to collection centres*, c^t_{zc}, may be lower than the

Table 5. Results for variations in parameter investment.

Parameter *investment*	Problem type			
	Maint	*ITS*	*Trans*	*Hold*
50% initial value	s1 c2 c4	s1 s3	s1 s3	s1 s3
Initial value	s1 c2 c4	s1 c2 c4	s1 s3	s1 s3
200% initial value	s1 c2 c4	s1 c2 c4	s1 s3	s1 s3

transportation cost per unit from customers directly to warehouses. Indeed, the return cost is zero if the return is the customer's responsibility. Since this cost, c^t_{zc}, may affect the use of collection centres, the model is tested with values ranging from 0 (no cost) up to the transportation cost from customers directly to warehouses, c^t_{zw}. The purpose of considering this cost is to determine whether or not this parameter promotes the establishment of collection centres in close proximity to customers. The results are shown in table 7.

4.1.2. *Analysis of results*

In this section, a brief description highlighting the major findings is presented.

- *Condition of used products affects the solution design*. The results for parameter g indicate that the percentage of products suitable for remanufacturing affects the network design. For a high number of used products in poor condition (unsuitable for remanufacture), warehouses were avoided due to the transportation penalty costs. In this case collection centres were preferred to sort products earlier in the supply chain. This result validates the combined analysis of forward and reverse flow. Considering them independently would result in a network design with more warehouses for the forward flow and

Table 4. Results for variations in parameter d.

Parameter d	Problem type				Sorting capacity	
	Maint	*ITS*	*Trans*	*Hold*	Offered	Required
15	s1 s3 c1 c4	s1 s3 c1 c4	s1 s3 c1 c4	s1 s3 c1 c4	100	94.5
14	s1 c2 c3	s1 s3 c2	s1 s3 c2	s1 s3 c2	90	88.5
13	s1 c3 c4	s1 s3 c2	s1 s3 c2	s1 s3 c2	90	81.9
12	s1 c1 c3	s1 s3 c1	s1 s3 c1	s1 s3 c1	80	75.6
11	s1 c2 c4	s1 s3	s1 s3	s1 s3	70	69.3
10	s1 c2 c4	s1 c2 c4	s1 s3	s1 s3	70	63.0
9	s1 c1 c4	s1 c1 c4	s1 c1 c4	s1 c1 c4	60	56.7
8	s1 c1 c4	s1 c1 c4	s1 c1 c4	s1 c1 c4	60	50.4
7	s1 c4	s1 c4	s1 c4	s1 c4	50	44.1
6	s1 c1	s1 c1	s1 c1	s1 c1	40	37.8
5	s1 c1	s1 c1	s1 c1	s1 c1	40	31.5

Table 6. Results for variations in parameter r.

Parameter r	Problem type				Sorting capacity	
	Maint	*ITS*	*Trans*	*Hold*	*Offered*	*Required*
1	s1 c2 c4	s1 s3	s1 s3	s1 s3	70	70
0.9	s1 c2 c4	s1 c2 c4	s1 s3	s1 s3	70	63
0.8	s1 c1 c4	s1 c1 c4	s1 c1 c4	s1 c1 c4	60	56
0.7	s1 c4	s1 c4	s1 c4	s1 c4	50	49
0.6	s1 c4	s1 c4	s1 c4	s1 c4	50	42
0.5	s1 c1	s1 c1	s1 c1	s1 c1	40	35
0.4	s1	s1	s1	s1	30	28
0.3	s1	s1	s1	s1	30	21
0.2	s1	w1 c2	s1	s1	20, 30	14
0.1	w1 c1	w1 c1	w1 c1	w1 c1	10	7
0	w1	w1	w1	w1	0	0

more collection centres for the reverse flow – clearly a more expensive solution design.

- *Present loss can justify high long-term investments*. The importance of using present loss in the objective function was demonstrated in the horizon length results analysis. Present loss (based on PWM), using the interest rate that affects future operational costs, assigns a more accurate (higher) value to these costs. Therefore, it is more apt to justify solutions with high investment costs due to lower operational costs. For short planning horizons, investment costs dominate operational costs as the deciding factor. Thus, for short planning horizons, the use of present-loss methods yields no advantage over the use of simpler methods.

4.2. *Sensitivity analysis results*

A sensitivity analysis was performed in order to determine the sensitivity of the results to variations in the input data. Based on the results, the parameters are classified in one of three categories: high sensitivity, medium sensitivity and low sensitivity. Parameters with high sensitivity are parameters that, if estimated slightly incorrectly, may yield a different solution. Therefore, these parameters should be more accurately estimated. Medium sensitivity parameters are parameters that require moderately accurate estimation. Low sensitivity parameters are parameters that have a minimal impact on the solution design. Different problem types exhibit slightly different responses to variations in the parameters. Therefore, based on the results, the model sensitivity is summarized for each problem type. This classification is presented in table 8.

Table 7. Results for variations in parameter c^t_{zc}.

Parameter c^t_{zc}	Problem type			
	Maint	*ITS*	*Trans*	*Hold*
c^t_{zc} value	s1 c2 c4	s1 c2 c4	s1 s3	s1 s3
$\frac{3}{4}c^t_{zc}$ value	s1 c2 c4	s1 c2 c4	s1 s3	s1 s3
$\frac{1}{2}c^t_{zc}$ value	s1 c2 c4	s1 c2 c4	s1 s3	s1 s3
$\frac{1}{4}c^t_{zc}$ value	s1 c2 c4	s1 c2 c4	s1 c2 c4	s1 s3
0 (no cost)	s1 c2 c4	s1 c2 c4	s1 c2 c4	s1 s3

Table 8. Parameter classification with respect to model sensitivity.

Parameter sensitivity	Problem type			
	Maint	*ITS*	*Trans*	*Hold*
High	demand % returned	demand % returned	demand % returned	demand % returned
Medium		condition investment interest rate	transportation c^t_{zc} interest rate	
Low	condition horizon length interest rate investment tranportation c^t_{zc}	horizon length transportation c^t_{zc}	condition horizon length investment	conditions horizon length interest rate investment transportation c^t_{zc}

This analysis offers guidance as to which parameters are more critical in terms of accuracy. Generally, the model appears to be highly sensitive to demand and percentage of demand returned. Variations in both of these parameters affect the required sorting capacity of the network. Since capacity is predefined in data, solutions with different capacities correspond to different network designs. Therefore, efforts should be focused on accurate estimation of demand and percentage of demand returned.

4.3. *Conclusions by problem type*

Some general tendencies were observed with regard to problem type. In fact, the four problem types can be combined into two groups that behave similarly: *Maint/ITS and Trans/Hold*. This similarity can be explained by the fact that both maintenance and sorting costs depend on the number and capacities of facilities used, while transportation and holding costs depend on the quantities transported.

Generally, problem types *Maint* and *ITS* led to the use of collection centres and problem types *Trans and Hold* led to the use of warehouses. Insights into this behaviour are given below.

- *Problem type Trans leads to the use of warehouses*. Although high transportation costs increase the penalty for using warehouses (for the reverse flow of products in poor condition), problem type *Trans* tended to use warehouses. Warehouses are the only facilities that can be used in the forward flow. Therefore, the fewer the number of warehouses, the more centralized the network and the higher the forward transportation costs. So, in order to avoid extremely high transportation costs in the forward flow, the solution design tended to use more warehouses and consequently fewer collection centres. It is interesting to note that simultaneously considering both forward and reverse flows clearly affects the solution design. This result validates the combined analysis of forward and reverse flow. Considering them independently would result in a network design with more warehouses for the forward flow and more collection centres for the reverse flow – clearly a more expensive solution design.
- *Problem type Hold avoids the use of collection centres*. The use of collection centres incurs extra holding costs – products stored at a collection centre must subsequently be stored at a warehouse. On the other hand, products transported directly to a warehouse incur a holding cost only once. Since problem type *Hold* has an extremely high holding cost, it tended to avoid collection centres.
- *Problem type Maint avoids the use of warehouses*. The maintenance cost at collection centres is lower than at warehouses (because collection centres do not handle the forward flow). In problem type *Maint*, with maintenance costs extremely high, this aspect is exacerbated. As a result, the model tended to minimize the number of warehouses, and select collection centres instead.
- *Problem type ITS avoids the use of warehouses*. The high investment cost associated with warehouses appears to be the primary reason for using collection centres. As with other problem types, long planning horizons may change the solution and favour larger investments.

Some exceptions to these general tendencies were observed. With low values of g (percentage of products in good condition), collection centres are preferred over warehouses. Also, for parameters d (demand), and r (percentage of demand returned), the result is primarily dependent upon the required capacity. Therefore, the above tendencies did not apply in these situations as well.

5. Conclusions and future work

The significant contributions of this work are as follows:

- *The condition of used products affects the solution design*. The literature observes that the existence of sorting facilities in close proximity to customers may reduce the transportation costs by not transporting products in poor condition that are unsuitable for remanufacture. Because of this, the condition of used products is included as a parameter in the model, for the purpose of testing whether or not it affects the network design. The results clearly indicate that the percentage of products in good condition affects the network design. For a high number of used products in poor condition, the solution design is more likely to avoid warehouses due to the penalized transportation costs. Therefore, the condition of used products is a parameter that should be considered in any product recovery network design model.
- *Present loss can justify high long-term investments*. The investment costs are very large one-time costs. Operational costs are smaller per-cycle costs (in the future) and therefore it is important to consider the time value of money, since it may have an effect on the ultimate decision made by the decision-maker. In reverse logistics literature, some authors do not consider the time value of money, some consider depreciation costs and some assume an equivalent cost. Investment worth methods

(although already used in forward location problems) have not yet been used in reverse logistics. To improve the accuracy of the model, particularly in the consideration of investment and future operational costs, the present worth method is applied. Results indicate that present loss (based on the present worth method), by using the interest rate that affects the future operational costs, yields a more accurate (higher) estimate of these costs. Therefore, higher investment costs are more easily justified due to lower operational costs.

- *A typical solution design is identified for each problem type*. Generally, if the maintenance or sorting costs are high, then the solution design tends to use collection centres. If the transportation or holding costs are high, then the solution design tends to use warehouses.

Through the course of performing this research, some areas for future work were identified. A penalty function is used to encourage the use of collection centres in close proximity to customers, avoiding additional transportation of products not suitable for remanufacture. However, for a very low percentage of products suitable for remanufacture, warehouses are used only for customers in close proximity and collection centres are used for the remaining customers – not necessarily reducing the costs for transportation of products not suitable for remanufacture. The penalty function could be refined to better reflect this intention. This research studied some of the product recovery issues. However, there are other issues, such as uncertainty in terms of timing, and quality and quantity of used products, that are worthwhile to be addressed. Including stochastic characteristics would allow improved understanding of problem dynamics. Since the disposer and re-use markets coincide, combined transportation could be used. In order to reduce transportation costs, the same trip in which products are delivered to a customer could be used to collect used products, thus minimizing empty trips. The model is dependent on the capacity defined in data. Although, in some cases, the capacity at each facility location is pre-defined, there may be other cases in which this restriction does not apply and capacity could be determined by the model.

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Appendix A: Complete formulation

The full mathematical formulation of the model is presented in this Appendix.

$$\min \mathrm{PL} = \text{investment cost} + \sum_{t=1}^{T} \text{operational cost} \cdot (1+I)^{-t} \tag{1}$$

subject to:

Flow Constraints
Opening Constraints
Installation Constraints
Capacity Constraints
Non-negativity and Binary Constraints

Objective function terms

$$\text{investment cost} = \text{opening} + \text{installation costs} \tag{2}$$

$$\text{operational cost} = \text{maintenance} + \text{sorting} + \text{holding} + \text{transportation costs} \tag{3}$$

$$\text{opening cost} = \sum_{w \in W} c_w^{ow} \cdot x_w + \sum_{c \in C} c_c^{oc} \cdot y_c \tag{4}$$

$$\text{installation cost} = \sum_{w \in W} c_w^{i} \cdot s_w \tag{5}$$

$$\text{maintenance cost} = \sum_{w \in W} c_w^{mw} \cdot x_w + \sum_{c \in C} c_c^{mc} \cdot y_c \tag{6}$$

$$\text{sorting cost} = \sum_{w \in W} c_w^{s} \cdot s_w \tag{7}$$

$$\text{holding cost} = \sum_{w \in W} h_w^{w} \cdot \left(\sum_{m \in M} \frac{q_{mw}}{2} + \sum_{z \in \mathcal{Z}} \frac{q_{zw} \cdot g}{2} + \sum_{c \in C} \frac{q_{cw}}{2} \right) \tag{8}$$

$$+ \sum_{c \in C} h_c^{c} \left(\sum_{z \in \mathcal{Z}} \cdot \frac{q_{zc} \cdot g}{2} \right) \tag{9}$$

$$\text{transportation cost} = \sum_{i} \sum_{j} q_{ij} \cdot b_{ij} \cdot c_{ij}^{t} + \sum_{z \in \mathcal{Z}} \sum_{w \in W} q_{zw} \cdot b_{zw} \cdot c_{zw}^{t} \cdot (1 + (1 - g)) \tag{10}$$

where pair (i, j) is any of (m, w), (w, z), (z, w), (z, c) or (c, w).

Constraints

Flow Constraints

$$\sum_{w \in W} q_{mw} \leq a_m \quad \forall m \in M \tag{11}$$

$$\sum_{m \in M} q_{mw} = \sum_{z \in \mathcal{Z}} q_{wz} \quad \forall w \in W \tag{12}$$

$$\sum_{w \in W} q_{wz} = d_z \quad \forall z \in \mathcal{Z} \tag{13}$$

$$\sum_{w \in W} q_{zw} + \sum_{c \in C} q_{zc} = r_z \cdot \sum_{w \in W} q_{wz} \quad \forall z \in \mathcal{Z} \tag{14}$$

$$\sum_{z \in \mathcal{Z}} q_{zc} \cdot g = \sum_{w \in W} q_{cw} \quad \forall c \in C \tag{15}$$

$$\sum_{c \in C} q_{cw} + \sum_{z \in \mathcal{Z}} q_{zw} \cdot g = \sum_{m \in M} q_{wm} \quad \forall w \in W \tag{16}$$

Opening Constraints:

$$q_{wj} \leq L \cdot x_w \quad \forall w \in W, j \in \mathcal{Z}, M \tag{17}$$

$$q_{iw} \leq L \cdot x_w \quad \forall i \in M, \mathcal{Z}, C, w \in W \tag{18}$$

$$q_{cw} \leq L \cdot y_c \quad \forall c \in C, w \in W \tag{19}$$

$$q_{zc} \leq L \cdot y_c \quad \forall z \in \mathcal{Z}, c \in C \tag{20}$$

Installation Constraints:

$$x_w \geq s_w \quad \forall w \in W \tag{21}$$

Inspection Constraints:

$$q_{zw} \leq L \cdot s_w \quad \forall w \in W \tag{22}$$

Capacity Constraints:

$$\sum_{z \in \mathcal{Z}} q_{zw} \leq k_w \quad \forall w \in W \tag{23}$$

$$\sum_{z \in \mathcal{Z}} q_{zc} \leq k_c \quad \forall c \in C \tag{24}$$

Non-negativity and Binary Constraints:

$x_w \in \{0, 1\} \quad \forall w \in W$
$y_c \in \{0, 1\} \quad \forall c \in C$
$s_w \in \{0, 1\} \quad \forall w \in W$
$q_{ij} \geq 0 \quad \forall i, j \in M, W, \mathcal{Z}, C$
where L is a very large number.

Appendix B: Data

This appendix describes the data used in this research. Figure 2 in section 4 represents the location of existing sites and potential new facilities. Table 9 shows the sorting capacity values used in the example. The values of parameters were defined based on data presented in the literature (Jayaraman *et al.* 1999, Spengler *et al.* 1997). The investment and operational facilities costs were defined proportionally to the sorting capacity (see Table 10 and 11). Costs at warehouses are higher than those at collection centres because the warehouses must

Table 9. Sorting capacity per potential facility.

Facility	Sorting capacity (thousands of units)
Warehouse 1	30
Warehouse 2	70
Warehouse 3	40
Collection centre 1	10
Collection centre 2	20
Collection centre 3	40
Collection centre 4	20

Table 10. Investment costs per thousand units of capacity.

Investment cost ($)	Per thousand units of capacity
Opening warehouse	250
Opening collection centre	175
Installation cost	50

Table 11. Per-unit operational costs for each problem type.

	Problem type			
Operational cost ($)	*Maint*	*ITS*	*Hold*	*Trans*
Warehouse maintenance (per thousand units of capacity)	30	15	15	15
Collection centre maintenance (per thousand units of capacity)	30	37.5	22.5	22.5
Sorting (per thousand units of capacity)	15	30	15	15
Holding (per thousand units)	15	15	30	15
Transportation (per thousand units per mile)	0.06	0.06	0.06	0.12

process the forward flow (from manufacturers to customers) in addition to the reverse flow. Also, collection centres are assumed to always have sorting capabilities. Therefore, the installation cost of the sorting capability is included in the opening cost of collection centres.

In order to define operational costs for each problem type, the following approach was used: 40% of the operational cost is assigned to the critical component (the component that defines the problem type). The remaining 60% is equally assigned to the other three components (20% each). Consequently, the highest component of the operational cost is chosen to be approximately twice that of each of the other three. The per-unit operational costs were defined to reflect these relationships. These values are presented in table 11. For example, for problem type *Hold*, the holding cost value used (30) is twice that of the values used in other problem types (15).

Table 12. Other parameters.

Other parameters	Value
Availability per manufacturer (thousands of units)	70
Demand per customer zone (thousands of units)	10
Percentage of products in good condition	0.9 (90%)
Interest rate	0.11 (11%)
Percentage of returned demand	0.9 (90%)
Horizon length (years)	20

As shown in table 11, the collection centre maintenance cost does not have the same value for problem types *ITS, Hold and Trans*. Furthermore, the value used for problem type *Maint* is not twice that of the other three, as one might expect. Again, since collection centres are assumed to always have sorting capabilities, the sorting cost is included in the maintenance cost for these facilities. Consequently, for problem type *ITS* (when sorting cost is high) maintenance cost for collection centres is higher than for other problem types. Also, for problem type *Maint*, only the maintenance component is doubled (the embedded sorting cost remains unchanged). Therefore, the final value of the maintenance cost (30) is less than twice the value for problem types *Hold* and *Trans* (22.5). The remaining parameters, shown in table 12, are common to all four problem types.