Reverse Logistics Supply Chain Network Design: Models and Issues

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***Abstract*—Environmental concern from customers, government and international institution such as EU and others urge the manufacturer to take back their products after use. We address eight different network design configurations from which the manufacturer can select the design for their reverse logistics system based on their requirements. The dominant literatures on reverse logistics network design are based on mixed integer program model and few center around subjective decision making approach like analytic hierarchy process, but none has integrated both approaches in the same context. In this paper, we explore two different methodologies- mixed integer program model and analytic hierarchy process, for the same business scenario using the real data and further conduct the extensive sensitivity analysis for three levels of volume i.e. high, medium and low. In addition, we discuss practical implications of our findings from two different methodologies and we provide insights on network design for reverse logistics system.**

***Keywords*—** *reverse logistics, closed loop, network design, analytic hierarchy process*

1 Introduction

Scarcity of natural resources will become inevitable, so manufacturers have started to work on recovering the goods to be reused with some engineering improvements for future customer. Management have to take into account various factors and many scenarios before finalizing the appropriate logistics network system. One of the major decisions is the facility location for (i) collecting the product from their own store or from a third party collection store, (ii) inspecting and sorting at a warehouse that is also used for forward distribution or at a dedicated collection centre, and (iii) reprocessing at the factory of the original or specialized-third-party facility. Figure 1 illustrates eight sets of network designs for the reverse logistics, from which the manufacturer can choose the best one, depending upon its requirements. These network designs are derived from the case studies reviewed in the next section.

The general recovery network model proposed by Fleischmann [1] is a mixed integer program that includes supply push constraints rather than being entirely driven by demand pull constraints. In this study, we extend this model by including capacity constraints in a single production version under uncertainty. The multiple return flow dispositions and the possible interactions between forward and reverse channels are the additional characteristics of our formulation. The analytic hierarchy process of Saaty [2] and [3] (AHP) is the process of systematic rationality to consider the problem as a whole, and to study the simultaneous interaction of its components within a hierarchy. We further discuss about these two scientific methodologies in Section 3. We have organized our research on how the reverse logistics network design should be established, while other logistics issues such as inventory management (see Fleischmann [1]) and lead time (see Lieckens and Vandaele [4]) are not considered in this research. There is a lack of research that integrates both the integer programming and AHP approach for the same scenario. Although the integer programming can act as an important tool for optimizing the logistics network of a company, from the practical point of view it may not be a feasible or affordable technique for all the companies. Especially, small firms and manufacturers may prefer a simplified subjective judgement technique.

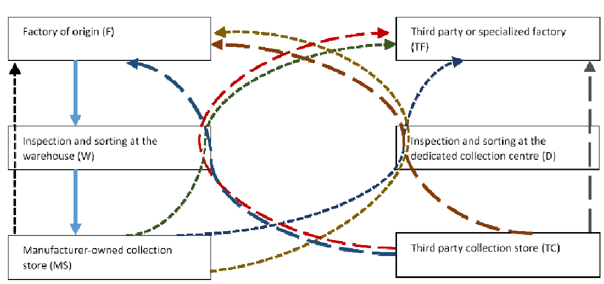

Figure 1. Schematic illustration of the research framework

2 Case study review

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In this section, we review the case studies categorized based on the type of network design companies have implemented for the reverse logistics system. The first network design (Design 1) uses the collection store owned by the manufacturer as a recovery point, inspecting and sorting them in the warehouse and finally transferring them to the factory of origin for reprocessing (MS-W-F network). Del Castillo & Cochran [5] focus on a centralized decision making system for return of containers, product distribution and production planning. Diaz & Fu [6] study a two-echelon repairable item inventory model with limited repair capacity, where the parts are subject to cycles and no new parts are brought from outside, assuming that all items can be repaired and that the affected card is exchanged and sent to a central repair facility. Linton & Johnson [7] developed a Decision Support System for the case of Nortol Network to assist their remanufacturing process, which permits better planning as well as controlling the interrelations between production and remanufacturing. Maslennikova & Foley [8] study an extensive Design-for-the-Environment program of Xerox Europe Ltd. Xerox use bar code labels to track packaging materials with the aim of preserving resources. To ensure that equipment and components do not end up in landfill sites, Xerox marks them with recycling symbols and reprocessing codes that explain the recycling and reuse potential. Similar to Xerox, McGavis [9] studies about the return of HP toner cartridges by the customer using a pre-paid UPS shipping label. They are centrally reviewed in Brisbane and after disassembly over 98% of the flow is used to remanufacture new toner cartridges. Toktay et al. [10] study the ordering policies for a single-use camera of Kodak. The returned cameras are dismantled and their flash circuit boards of every camera are used in the manufacturing of new products. A closed queuing network model is applied to decide on periodic ordering decisions with minimal costs for circuit board procurement, inventory and lost sales. Spengler et al. [11], who focuses on environmental friendly technologies due to higher disposal costs, describe two planning problems: (i) recycling and dismantling of industrial by-products, and (ii) product recycling at the end of their lifetime. Chang & Wei [12] discuss the recycling network for household waste and they deal with the allocation of recycling drop-off stations. They focus on constructing mechanized sorting installations to complete the recycling cycle. There are alternatives for improving efficiency and reducing costs by using correct container sizes, fewer workers, less glass breakage during collection, and better location of transfer stations in the integrated solid waste management system.

Design 2 selects the stores of the manufacturer as recovery points, inspecting at the warehouse and using third party or specialized factory for reprocessing (MS-W-TF network). Yender [13] studies the batteries recycling of EXIDE where the used and collected batteries are shipped to one of its regional lead-smelting operation. The damaged or leaking batteries are dispatched to third party waste haulers, and the rest are repaired and reused as spare part replacements. Fleischmann [1] classifies recovered items as used, unused and rotable spare parts. The used machines that have the potential for re-marketing are assigned for refurbishment, the others are dismantled to recover valuable parts. The remaining parts of used machines after selling to external parties are transferred to recycling subcontractors. Because of the short lifecycle the unused machines are disassembled and served as input to the production process. Thierry [14] proposes three reasons for centralizing reverse logistics process: (i) faster learning by experience; (ii) higher capacity utilization; and (iii) cost effective and better coordinated transportation of recyclable and disposable materials. Design 3 selects own collection stores, inspects the recovered items at the dedicated collection centre and reprocess in the factory of origin (MS-D-F network). Gupta & Chakrabotry [15] describe the processing of scrap generated during the production of glass. A deterministic mathematical model is presented to determine the optimal production lot size, taking into account the recycling activities. Krikke et al. [16] study the reverse chain of photocopiers and consider two strategies for the remanufacturing facility: (i) coinciding with the manufacturing facility; and (ii) transportation in low-wage countries. They evaluated the costs of both options, including the transportation effects. Rudi et al. [17] discusses the product recovery actions of National Insurance Administration (NNIA), who retrieves wheel chairs, hearing aids and similar products provided to disabled persons. The patient who no longer needs the equipment returns it to the Technical Aid Centre (TAC), a representative outlet of NNIA, from where it is sent to local external units for inspection, washing and storing. The local units wait for the final decision to refurbish it, either in-house or at an outsourcer, or to scrap it. Unlike Design 3, Design 4 uses a third party or specialized factory for reprocessing (MS-D-TF network). Design 5 uses third party sites for recovery points, warehouses for inspection and sorting and factory of origin for final reprocessing (TC-W-F network). The original factory is used for reprocessing if leakage of core knowledge must be avoided. Because of this requirement there are none real world case studies related to Design 5 in De Brito [18]. Unlike the Design 5, Design 6 selects a third party or specialized factory for reprocessing (TC-W-TF network). Klausner & Hendrickson [19] present a mathematical model that is used for determining the optimal buy back amount for continuous flows of remanufacturing power tools. The take back concept is based on reusing certain high value components and remanufacturing a certain fraction that is characterized by almost no technological obsolescence and low use intensity. Louwers et al. [20] study the case of carpet recycling and develop a mathematical model for supporting the design of selectimg locations for reprocessing taking depreciation costs into account. Nagel & Meyer [21] report that Franhofer IML has developed both a methodology and a corresponding software tool called EDR-RLog to support planning of integrated and cost-optimized take back and recovery. The authors claim that the use of EDR-RLog software improves the existing system from both an ecological and economic point of view [21]. Realff et al. [22] discuss the similar network structure of Louwers et al. [20] using the same technology in the USA. They classify reverse production problem into two distinct classes: (i) the functional chain of activities is carried out without removal of the product from its current location (e.g. repair, renovation or refurbishment or large fixed assets or expensive-to-move structures); and (ii) the product is removed and enters the functional chain where each reprocessing activity may be located in different places. Similar to Realff et al. [22] we focus on mathematical models for the class (ii). Footwear industry has a shorter life cycle, which involves more production of shoes and higher level of post-consumer waste. Nike is the first company to take measures for waste management [23]. The first recovery option is to recycle the shoes, followed by the distribution of worn or unwanted shoes to developing countries. This reuse and recycling program involves a series of collection points in retail centers where customers can deposit their worn out and discarded athletic shoes, which are then taken to a central recycling facility where they are shredded. The output can be used for tennis and basketball courts, play grounds and running tracks. Unlike the Design 5, Design 7 performs inspection and sorting activities at a dedicated collection centre instead of the warehouses (TC-D-F network). We refer to the same assumption made earlier under TC-W-F network for the non-availability of case studies under this network design. Even though we did not find any real world case studies under Design 5 and Design 7, we will continue use these designs for the analysis in Section 4. Design 8 is similar to the TC-D-F network, except that reprocessing is carried out by a third party or specialized factory (TC-D-TF network). Hong et al. [24] study the design of large scale reverse logistics system of electronics in the state of Georgia and classify the different reprocessing sites to be used based on the four demand sources: (i) demand from people within Georgia who buy refurbished equipment; (ii) group of recycling facilities interested in buying metal, plastic, CRT and other demanufacturerd materials; (iii) demand from residence and commercial users who are interested in buying refurbished commercial equipment; (iv) landfills where we can dispose of the non-hazardous trash that results from demanufacturing. The brief summary of all the reviewed case studies are presented in the tabular form in Table 1.

3 Methodology

In this section we briefly introduce our deterministic mixed integer programming model, and further analyse this model in the context of six different sets of scenarios. Finally, these results are compared with the analytic hierarchy process.

3.1 Deterministic model

Six different location sets are used in the network design (see Figure 1). The flow variables and parameters are categorized into forward and reverse flows.

I : Factory of origin
$\hat{I}$: Third party or specialized factory
J : Warehouse
$\hat{J}$: Inspection and sorting at dedicated collection centre
K : Manufacturer owned collection store
$\hat{K}$: Third party collection store
Set of locations:

Demand – forward flow:

x_{ijk}^{f} = demand served by factory i through warehouse j and transferred to customer center k

$$y_i^{ff} = \begin{cases} 1, & \text{if factory } i \text{ is open; } i \in I \\ 0, & \text{otherwise} \end{cases}$$

$$y_{jk}^{fw} = \begin{cases} 1, & \text{if warehouse } j \text{ serves customer } k; \quad j \in J, k \in K \\ 0, & \text{otherwise} \end{cases}$$

Supply - reverse flow:

x_{kji}^{r} = returns from customer center k through inspection center j and transferred to reprocessing factory i; $i \in I \cup \hat{I},\ J \cup \hat{J},\ K \cup \hat{K}$

$$y_k^{r} = \begin{cases} 1, & \text{if facility } a \text{ is open} \\ 0, & \text{otherwise} \end{cases}$$

with $a = k$ for collection center k $\left(k \in K \cup \hat{K}\right)$, $a = j$ for inspection and sorting center $j\left(j \in J \cup \hat{J}\right)$ and $a = i$ for reprocessing factory i $(i \in I \cup \hat{I})$

Reverse network open or close indicator:

$$a^{r} = \begin{cases} 1, & \text{if facility } a \text{ is open} \\ 0, & \text{if facility } b \text{ is open} \end{cases}$$

with $a=k$ for collection center $k\ (k\in K)$, $a=j$ for inspection and sorting center $j\,(j\in J)$ and $a=i$ for reprocessing factory i $(i\in I)$; $b=k$ for collection center $k\ (k\in\hat{K})$, $b=j$ for inspection and sorting center $j\,(j\in\hat{J})$ and $b=i$ for reprocessing factory i $(i\in\hat{I})$

Forward flow parameters:

fixed costs for opening :
f_i^{ff} = factory $i\in I$
f_j^{fw} = warehouse $j\in J$

maximum capacity :
m_i^{ff} = production of factory i; $i\in I$
m_j^{fw} = holding of warehouse j; $j\in J$

minimum capacity :
t_i^{ff} = production of factory i; $i\in I$
t_j^{fw} = holding of warehouse j; $j\in J$

c_{ijk}^{f} = transportation costs per unit of forward flow from i to j to k; $i\in I, j\in J, k\in K$
d_k = demand from customer zone k; $k\in K$

Reverse flow parameters:

fixed costs for opening :
f_i^{rf} = reprocessing factory $i\in I\cup\hat{I}$
f_j^{ri} = inspection and sorting center $j\in J\cup\hat{J}$
f_k^{rc} = collection center $k\in K\cup\hat{K}$

maximum capacity:
m_i^{rf} = reprocessing factory i; $i\in I\cup\hat{I}$
m_j^{ri} = inspection and sorting center j; $j\in J\cup\hat{J}$
m_k^{rc} = collection center k; $k\in K\cup\hat{K}$

minimum capacity:
t_i^{rf} = reprocessing factory i; $i\in I\cup\hat{I}$
t_j^{ri} = inspection and sorting center j; $j\in J\cup\hat{J}$
t_k^{rc} = collection center k; $k\in K\cup\hat{K}$

c_{kji}^{r} = transportation cost per unit of reverse flow from k to j to i; $k\in K\cup\hat{K}, j\in J\cup\hat{J}, i\in I\cup\hat{I}$

r_k = return from only the collection store of manufactuer k; $k\in K$
$\hat{r}_k$ = return from only the third party collection center k; $k\in\hat{K}$

The model is formulated as a cost minimization problem for reverse logistics. The objective function is defined in Eq.(A) while Eq.(1) to (26) are constraints to be satisfied.

$$\min \sum_{i\in I} f_i^{ff} y_i^{ff} + \sum_{j\in J} f_j^{fw} y_{jk}^{fw} + \sum_{i\in I\cup\hat{I}} f_i^{rf} y_i^{rf} + \sum_{j\in J\cup\hat{J}} f_j^{ri} y_j^{ri} + \sum_{k\in K\cup\hat{K}} f_k^{rc} y_k^{rc} + \sum_{i\in I}\sum_{j\in J}\sum_{k\in K} c_{ijk}^{f} x_{ijk}^{f} + \sum_{i\in I\cup\hat{I}}\sum_{j\in J\cup\hat{J}}\sum_{k\in K\cup\hat{K}} c_{kji}^{r} x_{kji}^{r} \tag{A}$$

s.t.:

$$\sum_{i\in I}\sum_{j\in J} x_{ijk}^{f} \ge d_k, \quad \forall\ k\in K \tag{1}$$
$$\sum_{i\in I\cup\hat{I}}\sum_{j\in J\cup\hat{J}} x_{kji}^{r} \ge r_k a^c, \quad \forall\ k\in K \tag{2}$$
$$\sum_{i\in I\cup\hat{I}}\sum_{j\in J\cup\hat{J}} x_{kji}^{r} \ge \hat{r}_k\left(1-a^c\right), \quad \forall\ k\in\hat{K} \tag{3}$$

$$\sum_{j\in J}\sum_{k\in K} x_{ijk}^{f} \le m_i^{ff} y_i^{ff}, \quad \forall\ i\in I \tag{4}$$
$$\sum_{j\in J}\sum_{k\in K} x_{ijk}^{f} \ge t_i^{ff} y_i^{ff}, \quad \forall\ i\in I \tag{5}$$
$$\sum_{i\in I}\sum_{k\in K} x_{ijk}^{f} \le m_j^{fw} y_{jk}^{fw}, \quad \forall\ j\in J \tag{6}$$
$$\sum_{i\in I}\sum_{k\in K} x_{ijk}^{f} \ge m_j^{fw} y_{jk}^{fw}, \quad \forall\ j\in J \tag{7}$$
$$\sum_{j\in J}\sum_{k\in K} x_{kji}^{r} \le m_i^{rf} y_i^{rf}, \quad \forall\ i\in I\cup\hat{I} \tag{8}$$
$$\sum_{i\in I}\sum_{j\in J} x_{kji}^{r} \ge t_i^{rf} y_i^{rf}, \quad \forall\ i\in I\cup\hat{I} \tag{9}$$
$$\sum_{i\in I}\sum_{k\in K} x_{kji}^{r} \le m_j^{ri} y_j^{ri}, \quad \forall\ j\in J\cup\hat{J} \tag{10}$$
$$\sum_{i\in I}\sum_{k\in K} x_{kji}^{r} \ge t_j^{ri} y_j^{ri}, \quad \forall\ j\in J\cup\hat{J} \tag{11}$$
$$\sum_{i\in I}\sum_{j\in J} x_{kji}^{r} \le m_k^{rc} y_k^{rc}, \quad \forall\ k\in K\cup\hat{K} \tag{12}$$
$$\sum_{i\in I}\sum_{j\in J} x_{kji}^{r} \ge t_k^{rc} y_k^{rc}, \quad \forall\ k\in K\cup\hat{K} \tag{13}$$
$$y_i^{rf} \le a^r, \quad \forall i\in I \tag{14}$$
$$y_i^{rf} \le 1-a^r, \quad \forall i\in\hat{I} \tag{15}$$
$$y_j^{ri} \le a^i, \quad \forall j\in J \tag{16}$$
$$y_j^{ri} \le 1-a^i, \quad \forall j\in\hat{J} \tag{17}$$
$$y_k^{rc} \le a^c, \quad \forall k\in K \tag{18}$$
$$y_k^{rc} \le 1-a^c, \quad \forall k\in\hat{K} \tag{19}$$

Table 1. Case study summary

Network Design		Ref.	Sender	Collect	Inspect	Reprocess	Recovery Options	Recovery Drivers		Case
								Sender	Manufacturer	
MS-W-F	Design 1	[5]	Consumer	Soft drinks retail store	Soft drink company	Soft drink company	Reuse	End-of-use	Economics	Reusable soft drinks glass bottle
		[6]	Caracas subway	Caracas subway	Caracas subway	Caracas subway	Repair	Service	Economics	Subway spare parts inventory management
		[7]	Customer	Customer service of Nortel	Central inspection by Nortel	Nortel (original factory)	Remanufacture	Service	Economics	Circuit board remanufacturing
		[8]	Customers	Xerox Europe (Customer Service)	Xerox Europe (Service Engineers)	Xerox Europe	Refurbish, Recycling	Service	Economics,	Remanufacturing of Electronic products
		[9]	Users of toner cartridge	HP store (transported by USP)	HP	HP	Recycling	End-of-use	Economics (and to put jobbers out of market)	Recycling of printer toner cartridges
		[10]	Consumer	Retail outlets (Photoshop)	Kodak	Kodak	Remanufacture	End-of-use	Economics (for cost savings)	Single use camera remanufacturing
		[11]	Steel industry	Steel industry	Steel industry	Steel industry	Recycling	Manufacture	Corporate citizenship	Steel by-products
		[12]	Household	Public authority	Public authority	Public authority	Recycling	End-of-life	Economics, legislations	Municipal curbside waste
		[14]	User	OPCOs	CRC	Original factory	Remanufacture	End-of-life (lease term)	Economics	Remanufacturing copier products
MS-W-TF	Design 2	[25]	UNISYS Customer	UNISYS	UNISYS	Secondary facility	Remanufacture	End-of-use	Economics	Printer toner cartridges recycling
		[13]	Household, company	Store/ outlet	Regional lead-smelting operations	Specialists (Different processors)	Recycling	End-of-life	Economics, legislative	Batteries recycling
		[1]	Business customer	Local operating companies, service engineers	National distributers, central stock locations	Specialized facility	Refurbish, repair, recycle	End-of-life	Economics, legislative	Reverse logistics of IBM

		[14]	User	OPCOs	CRC	Existing suppliers	Recycle	End-of-life (lease term)	Economics	Recycling of copier products
MS-D-F	Design 3	[16]	Local filial	OCE (local operating companies)	External inventory location	OCE	Remanufacture	End-of-use	Economics	Copier remanufacturing
		[15]	Glass producer	Glass producer	Glass producer	Glass producer	Recycling	Manufacture	Economics	Glass scrap recycling
		[17]	User	TAC representatives	Local external unit	TAC	Reuse, refurbish, recycle	Service (repair)	Economics	Wheelchair refurbishing
MS-D-TF	Design 4	[14]	User	OPCOs	OPCOs	OPCOs	Repairing	End-of-life (lease term)	Economics	Repairing of copier products
TC-W-TF	Design 6	[19]	Customer	Dealer	Specialized facility	Specialized facility	Remanufacture	End-of-life	Economics	Power tool remanufacturing
		[26]	Consumer	Municipal		Waste Company	Recycling		Legislation, economics	PC monitor recycling
		[20]	Household, business company	Municipalities	Specialists (RPC)	Specialized organization	Recycling	End-of-life	Legislation, economics	Carpet recycling
		[21]	Household, industry	Dealer and specialized	Specialized facility (for disassembly)	Recovery plant	Remanufacture, recycling	End-of-life	Legislation, economics	Refrigerator remanufacturing
		[22]	Business customer	Carpet dealers	Specialists (RPC)	Dupont	Recycling	End-of-life	Economics	Carpet recycling
		[23]	Consumer	Shoe dealers	Specialized facility	Specialized facility	Resale(to developing countries), Recycling	End-of-life	Economics, environmental	Footwear recycling
TC-D-TF	Design 8	[24]	Residence, business houses	Municipal collection sites	Municipal sites	Specialized processing sites	Recycle, refurbish, remanufacture	End-of-life	Legislative, economics	Regional e-scrap processing infrastructure

$$\sum_{i\in I\cup\hat{I}}\sum_{j\in J\cup\hat{J}}\sum_{k\in K}x_{kji}^{r} \le \sum_{i\in I}\sum_{j\in J}\sum_{k\in K}x_{ijk}^{f} \quad (20)$$

$$\sum_{i\in I\cup\hat{I}}\sum_{j\in J\cup\hat{J}}\sum_{k\in \hat{K}}x_{kji}^{\hat{r}} \le \sum_{i\in I}\sum_{j\in J}\sum_{k\in K}x_{ijk}^{f} \quad (21)$$

$$x_{ijk}^{f} \ge 0, \quad \forall i\in I,\ j\in J,\ k\in K \quad (22)$$

$$x_{kji}^{r} \ge 0, \quad \forall i\in I\cup\hat{I},\ j\in J\cup\hat{J},\ k\in K\cup\hat{K} \quad (23)$$

$$y_i^{ff}, y_{jk}^{fw} \in \{0,1\},\ \forall i\in I,\ j\in J,\ k\in K \quad (24)$$

$$y_i^{rf}, y_j^{ri}, y_k^{rc} \in \{0,1\},\ \forall i\in I\cup\hat{I},\ j\in J\cup\hat{J},\ k\in K\cup\hat{K} \quad (25)$$

$$a^r, a^i, a^c \in \{0,1\} \quad (26)$$

In the objective function, the first two terms indicate the fixed cost for the forward flow, the following three terms represent the cost for the reverse flow and the last two terms are for the cost of transportation and processing in forward and reverse flow respectively. Constraints (1) to (3) handle the customer demand, also taken into account goods returning back. Constraint (1) ensures that the forward flow is at least equal to the demand from each customer zone. Constraints (2) and (3) determine the reverse flow from collection store of the manufacturer and the third party owner respectively. These constraints are either-or constraints, thus both recovery points (manufacturer and third party) cannot take place at the same time for a single product reverse flow and prevents collection of the returns twice. Constraints (4) to (7) limit the capacity to a feasible interval for the forward flow in the factories and warehouses that are open. Constraints (8) to (13) are similar for the reverse flow in the reprocessing factories, inspection centers and collection stores that are open. Since only one node can be used in each stage of the reverse process (see Figure 1), we have used six sets of either-or constraints (14) to (19). The corresponding vectors a^r, a^i and a^c represent variables for active locations of reprocessing plants, inspection/sorting facilities and collection stores. Constraints (20) and (21) model the required coordination between demand and supply, where the forward flow must be greater than the reverse flow. The possible gap represents products that have not been reversed and the production of new products. Constraints (22) to (26) refer to integral and binary requirements. This deterministic model can be used for the formulation of either open loop networks (only return flows) or closed loop networks (both demand and return are handled). In a closed loop network we have non-zero demand and non-zero return parameters (i.e., $d_k, r_k, \hat{r}_k \neq 0$), whereas in an open loop network this is only true for the return parameters, so we have to exclude demand and supply coordinating constraints (20) and (21). Furthermore, manufacturer owned and third party collection sites are not necessarily required to have comparable return quantities because their number of collection stores as well as their respective return volumes may be different. As a result, parameters r_k and $\hat{r}_k$ should be set in such a way that total returns are always the same and independent of the selected option.

3.2 Scenario-based model

In order to incorporate the uncertainty into the deterministic approach, we propose to add an extensive scenario analysis. If Ω stands for the set of all possible scenarios, then the problem can be formulated for a particular scenario $w \in \Omega$ [27]

$$\min \ fy + c_w x \quad (B)$$

$$\text{s.t.:} \quad A_w x \le a_w \quad (27)$$

$$B_w x \le C_y \quad (28)$$

$$y \in \{0,1\} \quad (29)$$

$$x \ge 0 \quad (30)$$

where A_w, B_w and C_y are matrices and a_w is a vector . The binary variables are included in vector y, the continuous variables in the vector x. The vector f stands for the fixed costs of opening facilities and c_w represents the remaining coefficients of the objective function. We have the following sets for the scenario based model:

x_{ijkw}^{f} = demand served by i through j and transferred to k for scenario w; $i\in I, j\in J, k\in K, w\in\Omega$

x_{kjiw}^{r} = returns from k through j and transferred to i for scenario w; $i\in I\cup\hat{I}, j\in J\cup\hat{J}, k\in K\cup\hat{K}, w\in\Omega$

π_w = probability of scenario $w\in\Omega$

d_{kw} = demand of customer k for scenario w; $k\in K, w\in\Omega$

r_{kw} = returns from customer zone k for scenario w; $k\in K, w\in\Omega$

$\hat{r}_{kw}$ = returns from customer zone k for scenario w; $k\in \hat{K}, w\in\Omega$

$$min\sum_{i\in I} f_i^{ff} y_i^{ff} + \sum_{j\in J} f_j^{fw} y_{jk}^{fw} + \sum_{i\in I\cup\hat{I}} f_i^{rf} y_i^{rf} + \sum_{j\in J\cup\hat{J}} f_j^{ri} y_j^{ri} + \sum_{k\in K\cup\hat{K}} f_k^{rc} y_k^{rc} + \sum_{w\in\Omega}\pi_w \left[\begin{array}{c}\sum_{i\in I}\sum_{j\in J}\sum_{k\in K} c_{ijk}^{f} x_{ijk}^{f} + \\ \sum_{i\in I\cup\hat{I}}\sum_{j\in J\cup\hat{J}}\sum_{k\in K\cup\hat{K}} c_{kji}^{r} x_{kji}^{r}\end{array}\right] \quad (C)$$

s.t.

$$\sum_{i\in I}\sum_{j\in J} x_{ijkw}^{f} \ge d_{kw}, \quad \forall\ k\in K\ , w\in\Omega \quad (31)$$

$$\sum_{i\in I\cup\hat{I}}\sum_{j\in J\cup\hat{J}} x_{kjiw}^{r} \ge r_{kw} a^c, \quad \forall\ k\in K\ , w\in\Omega \quad (32)$$

$$\sum_{i\in I\cup\hat{I}}\sum_{j\in J\cup\hat{J}} x_{kjiw}^{r} \ge \hat{r}_{kw}\left(1-a^c\right), \quad \forall\ k\in \hat{K}, w\in\Omega \quad (33)$$

$$\sum_{j\in J}\sum_{k\in K} x_{ijkw}^{f} \le m_i^{ff}\, y_i^{ff}, \qquad \forall\ i\in I\ , w\in\Omega \tag{34}$$
$$\sum_{j\in J}\sum_{k\in K} x_{ijkw}^{f} \ge t_i^{ff}\, y_i^{ff}, \qquad \forall\ i\in I\ , w\in\Omega \tag{35}$$
$$\sum_{i\in I}\sum_{k\in K} x_{ijkw}^{f} \le m_j^{fw}\, y_{jk}^{fw}, \qquad \forall\ j\in J\ , w\in\Omega \tag{36}$$
$$\sum_{i\in I}\sum_{k\in K} x_{ijkw}^{f} \ge t_j^{fw}\, y_{jk}^{fw}, \qquad \forall\ j\in J\ , w\in\Omega \tag{37}$$

$$\sum_{j\in J}\sum_{k\in K} x_{kjiw}^{r} \le m_i^{rf}\, y_i^{rf}, \qquad \forall\ i\in I\cup\hat{I}\ , w\in\Omega \tag{38}$$
$$\sum_{i\in I}\sum_{j\in J} x_{kjiw}^{r} \ge t_i^{rf}\, y_i^{rf}, \qquad \forall\ i\in I\cup\hat{I}\ , w\in\Omega \tag{39}$$
$$\sum_{i\in I}\sum_{k\in K} x_{kjiw}^{r} \le m_j^{ri}\, y_j^{ri}, \qquad \forall\ j\in J\cup\hat{J}\ , w\in\Omega \tag{40}$$
$$\sum_{i\in I}\sum_{k\in K} x_{kjiw}^{r} \ge t_j^{ri}\, y_j^{ri}, \qquad \forall\ j\in J\cup\hat{J}\ , w\in\Omega \tag{41}$$
$$\sum_{i\in I}\sum_{j\in J} x_{kjiw}^{r} \le m_k^{rc}\, y_k^{rc}, \qquad \forall\ k\in K\cup\hat{K}, w\in\Omega \tag{42}$$
$$\sum_{i\in I}\sum_{j\in J} x_{kjiw}^{r} \ge t_k^{rc}\, y_k^{rc}, \qquad \forall\ k\in K\cup\hat{K}\ , w\in\Omega \tag{43}$$

$$y_i^{rf} \le a^r, \qquad \forall i\in I \tag{44}$$
$$y_i^{rf} \le 1-a^r, \qquad \forall i\in \hat{I} \tag{45}$$
$$y_j^{ri} \le a^i, \qquad \forall j\in J \tag{46}$$
$$y_j^{ri} \le 1-a^i, \qquad \forall j\in J \tag{47}$$
$$y_k^{rc} \le a^c, \qquad \forall k\in K \tag{48}$$
$$y_k^{rc} \le 1-a^c, \qquad \forall k\in \hat{K} \tag{49}$$
$$\sum_{w\in\Omega}\pi_w\left[\sum_{i\in I\cup\hat{I}}\ \sum_{j\in J\cup\hat{J}}\ \sum_{k\in K} x_{kji}^{r}\right] \le \sum_{i\in I}\sum_{j\in J}\sum_{k\in K} x_{ijk}^{f} \tag{50}$$
$$\sum_{w\in\Omega}\pi_w\left[\sum_{i\in I\cup\hat{I}}\ \sum_{j\in J\cup\hat{J}}\ \sum_{k\in \hat{K}} x_{kji}^{\hat{r}}\right] \le \sum_{i\in I}\sum_{j\in J}\sum_{k\in K} x_{ijk}^{f} \tag{51}$$

$$x_{ijkw}^{f} \ge 0, \quad \forall i\in I,\ j\in J,\ k\in K\ ,\quad w\in\Omega \tag{52}$$
$$x_{kjiw}^{r} \ge 0, \quad \forall i\in I\cup\hat{I},\ j\in J\cup\hat{J},\ k\in K\cup\hat{K}\ ,\ w\in\Omega \tag{53}$$
$$y_i^{ff}, y_{jk}^{fw} \in \{0,1\}, \quad \forall i\in I,\quad j\in J,\quad k\in K \tag{54}$$
$$y_i^{rf}, y_j^{ri}, y_k^{rc} \in \{0,1\}, \forall i\in I\cup\hat{I},\ \ j\in J\cup\hat{J},\ \ k\in K\cup\hat{K} \tag{55}$$
$$a^r, a^i, a^c \in \{0,1\} \tag{56}$$

We assume that only the demand and return parameters are extended to represent scenarios with three volume levels, i.e. High, Medium and Low. Similar to Salema et al. [27], we set the scenario probability values at respectively 75%, 15% and 10%. This model is strategically used for the optimization of the facility location solely based on fixed opening costs and variable unit transportation costs.

3.3 Analytic hierarchy process

The methodology and different steps of conducting an analytic hierarchy process are illustrated in Figure 2 and briefly described below.

3.3.1 Structure

The classification of Theresa and Zelda [28] with six critical criteria for facility location (i.e.: (i) recycle, (ii) warehouse inspection, (iii) shipping scrap, (iv) original factory reprocessing, (v) proprietary knowledge, (vi) customer interactions, and three additional criteria: (vii) fixed costs, (viii) tax structure and (ix) income and population density) are divided into two major groups: cost savings and future business relationships. The alternatives are the eight network designs that we have derived from the case study review in Section 2. The cost saving criterion may play a dominant role if the manufacturer decides to give more weight to cost reductions at different stages compared to future business relationships. On the contrary, future business relationship criterion may have higher weight if focused on maintaining direct relationship with customers.

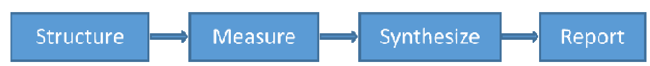

Figure 2. Stages of analytic hierarchy process

3.3.2 Measure

The second stage is to derive priorities for the relative importance of the objective as well as the relative preferences for the alternatives with respect to the objective. We have followed the benchmarking mode, which ranks alternatives by including a known alternative in a group and comparing it against the other. We assign a ranking value of 1 to the benchmarking element followed by respective weights to other elements based on their importance. Figure 3 illustrates the flow of different activities in the second stage.

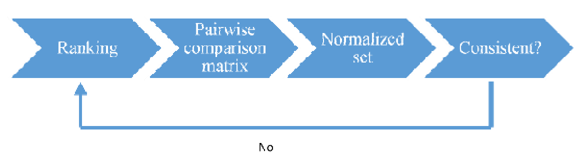

Figure 3. Activities in 2nd stage of analytic hierarchy process

Using Saaty scale [2] we rank each criterion and its sub-criterion that ranges from 1 (least important) to 9 (most important). Based on the case study review, we have developed a ranking that reflects the relationship between the network design alternatives and nine sub-criteria (see Table 2). The different recovery objectives from the case study review are either to repair, remanufacture and refurbish returned items or to recycle them into raw materials. The cost of recycling can be reduced using third party collection points and specialized or third party reprocessing facilities. As revealed in 6 out of 24 case studies, using third party collection stores for recycling is favoured by most manufacturers as it has a high potential for cost savings. Furthermore, 12 case studies have used a third party or a specialized factory for reprocessing, from which 10 are used for recycling. Similarly, 12 case studies have used the original factory for reprocessing, from which 6 are used for recycling. Thus, producers will not have significant differences in cost savings if recycling takes place in the factory of origin or a third party facility. However, there exists some potential for cost savings if it is recycled in third party facility as no investments must be made in setting up a specialized plant for recycling in the original factory. We assign ranking value 7 for using third party collection stores since this recovery option is preferred when the producer has no intention to control reverse logistics processes and/or to protect proprietary knowledge of products. There is no need for additional effort to develop direct customer relationships and to protect core product knowledge if the producer opt for recycling, while using third party collection points will further help to share the total costs among producers. The network design using both third party collection points and third party reprocessing facility are highly favoured for recycling the recovered products, thus we assign ranking value 9 when both options are used. 20 case studies adopt inspection and sorting activities at the warehouse (ranking value 6), while the remaining 4 case studies perform this at their dedicated collection center. Installing inspection equipment in few warehouses will costs less than installing it in each collection points. Two out of 24 case studies deal with shipping scrap and inspection activities at the collection points. Louwers et al. [20] study carpet recycling and propose a mathematical model that focuses on minimizing costs through early disposal of scrap before it is sent to reprocessing, while further reducing the important share of transportation costs. As a result, we assign ranking value 9 to the network design that use collection points for inspection. Twelve case studies with recovery options except recycling use the original factory for reprocessing. However, large manufacturers, like glass producer of India [15], Hewlett Packard [9], steel industry of Germany [11] and public authority [12] use the original factory for recycling in 4 case studies, which is not within reach for small and medium sized manufacturers.In two case studies, remanufacturing of electronic products [8] and wheelchair refurbishment [17] , the original factory is used for joint recovery options in addition to recycling. This clearly demonstrates that the original factory is used for repairing, remanufacturing and refurbishing. The costs for reprocessing can be reduced through outsourcing to a third party or a specialized factory instead of installing equipment and training employees in the original factory, so we assign ranking value 5 to the network design that uses the original factory for reprocessing.

Fixed costs are included in the facility location model, except when the associated process is outsourced to a third party. We assign ranking value 7 to the design that uses a third party factory, which is higher than the ranking value 3 assigned to the design that uses third party collection points because more costs are carried by the manufacturer for reprocessing than collection. The manufacturer tends to be operational where the tax burden is low and where it is possible to outsource services to a third party. The same reasoning and ranking values of fixed costs apply to this sub-criterion. Using own collection points (ranking value 7) and the original factory for reverse processes (ranking value 3) help to protect the core knowledge of the product and maintain full logistical control. We use ranking value 9 for designs that uses both options. Since own collection stores with direct customer relationship are important, we assign it ranking value 9. If the population is dense and the income trend is high to sell products, manufacturers are eager to open their own recovery store in that customer zone, so we assign it ranking value 9. Most case studies treat reverse logistics network designs based on quantitative models, so we assign the ranking for the last three critical factors based on the literature review of Fleischmann [1], Thierry et al. [14] and De Brito [18]. We ask refer to Saaty [2] and [3] for the procedure to create a pairwise comparison matrix. Next, we generate a priority vector, also described as a normalized set of a pairwise matrix (see Table 3). It reveals the priority of the node in the relevant layer of the hierarchy. The indices c_1 to c_6 refer to the ranking value of 6 sub-criteria for cost savings, V_1^c refers to the normalized vector of the first cost savings' criterion, i.e. recycle until V_6^c for the normalized vector of sub-criterion 6, i.e. tax structure. Maximum eigen-value (λ_{max}), consistency index (*CI*) and consistency ratio (*CR*) are factors to check the consistency of the pairwise matrix [2]. Next, we divide each of the row totals R_i^c by the corresponding entry from the normalized set (i.e. $R_i^c \div V_i^c = \zeta_i$). The maximum eigen-value (λ_{max}) is derived as follows:

$\lambda_{max} = \frac{\sum_{i=1}^{n} \zeta_i}{n} = \frac{\sum_{i=1}^{6} \zeta_i}{6}$ for the cost savings matrix.

$\lambda_{max} = \frac{\sum_{i=7}^{n} \zeta_i}{n} = \frac{\sum_{i=7}^{9} \zeta_i}{3}$ for the future business relationship matrix.

Consistency index- is the degree of consistency of our judgement proposed by Saaty [2]:

$$CI = \frac{\lambda_{max} - n}{n - 1}$$

Table 2. Relationship between network design and criteria

Network design	Recycle	Warehouse inspection	Shipping scrap	Original factory reprocess	Fixed costs	Tax structure	Proprietary knowledge	Customer interactions	Income and population density
1		6		5			9	9	9
2	3	6			7	7	7	9	9
3			9	5			9	9	9
4	3		9		7	7	7	9	9
5	7	6		5	3	3	3		
6	9	6			9	9			
7	7		9	5	3	3	3		
8	9		9		9	9			

Table 3. Eigen-value calculation

Cost Savings	Normalized set or priority vector V_i^c	Recycle c_1	Warehouse Inspection c_2	Shipping scrap c_3	Original factory Reprocessing c_4	Fixed costs c_5	Tax structure c_6	Row totals R_i^c
Recycle c_1	$V_1^c = c_1/\sum_{i=1}^{6} c_i$	$(\frac{c_1}{c_1})V_1^c$	$(\frac{c_1}{c_2})V_2^c$	$(\frac{c_1}{c_3})V_3^c$	$(\frac{c_1}{c_4})V_4^c$	$(\frac{c_1}{c_5})V_5^c$	$(\frac{c_1}{c_6})V_6^c$	$\sum_{i=1}^{6} \frac{c_1 V_i^c}{c_i}$
Warehouse Inspection c_2	$V_2^c = c_2/\sum_{i=1}^{6} c_i$	$(\frac{c_2}{c_1})V_1^c$	$(\frac{c_2}{c_2})V_2^c$	$(\frac{c_2}{c_3})V_3^c$	$(\frac{c_2}{c_4})V_4^c$	$(\frac{c_2}{c_5})V_5^c$	$(\frac{c_2}{c_6})V_6^c$	$\sum_{i=1}^{6} \frac{c_2 V_i^c}{c_i}$
Shipping scrap c_3	$V_3^c = c_3/\sum_{i=1}^{6} c_i$	$(\frac{c_3}{c_1})V_1^c$	$(\frac{c_3}{c_2})V_2^c$	$(\frac{c_3}{c_3})V_3^c$	$(\frac{c_3}{c_4})V_4^c$	$(\frac{c_3}{c_5})V_5^c$	$(\frac{c_3}{c_6})V_6^c$	$\sum_{i=1}^{6} \frac{c_3 V_i^c}{c_i}$
Original factory Reprocessing c_4	$V_4^c = c_4/\sum_{i=1}^{6} c_i$	$(\frac{c_4}{c_1})V_1^c$	$(\frac{c_4}{c_2})V_2^c$	$(\frac{c_4}{c_3})V_3^c$	$(\frac{c_4}{c_4})V_4^c$	$(\frac{c_4}{c_5})V_5^c$	$(\frac{c_4}{c_6})V_6^c$	$\sum_{i=1}^{6} \frac{c_4 V_i^c}{c_i}$
Fixed costs c_5	$V_5^c = c_5/\sum_{i=1}^{6} c_i$	$(\frac{c_5}{c_1})V_1^c$	$(\frac{c_5}{c_2})V_2^c$	$(\frac{c_5}{c_3})V_3^c$	$(\frac{c_5}{c_4})V_4^c$	$(\frac{c_5}{c_5})V_5^c$	$(\frac{c_5}{c_6})V_6^c$	$\sum_{i=1}^{6} \frac{c_5 V_i^c}{c_i}$
Tax structure c_6	$V_6^c = c_6/\sum_{i=1}^{6} c_i$	$(\frac{c_6}{c_1})V_1^c$	$(\frac{c_6}{c_2})V_2^c$	$(\frac{c_6}{c_3})V_3^c$	$(\frac{c_6}{c_4})V_4^c$	$(\frac{c_6}{c_5})V_5^c$	$(\frac{c_6}{c_6})V_6^c$	$\sum_{i=1}^{6} \frac{c_6 V_i^c}{c_i}$

For each matrix of size n, Saaty [2] generated a random matrix with its mean called 'Random Consistency'. The comparison between the *CI* based on our judgement and the random consistency developed by Saaty [2] is the consistency ratio:

$$CR = \frac{CI}{Random\ Consistency}$$

CR less than 0.1 is acceptable while larger values require the decision maker to reduce the inconsistencies by revising judgements [2].

3.3.3 Synthesize

From the pairwise comparison matrix in previous step, we generate 9 normalized sets or column vectors with respect to alternatives V^{A^1} to V^{A^9}. In each matrix there are 8 elements referring to eight network designs. The matrices V^{A^1} to V^{A^6} relate to the cost savings subcriteria and the remaining matrices V^{A^7} to V^{A^9} relate to the future business relationships sub-criteria. We combine each column vector of cost savings sub-criteria and create one single matrix of size 8×6, multiplied by column vector V^C. This generates a solution with respect to cost savings. Similarly, for future business relationships, we use V^F to multiply the new matrix that is formed by combining three column vectors associated with three future business relationships sub-criteria (V^{A^7} to V^{A^9}). We form a single matrix by combining matrix *C* and matrix *F*, multiplied by V^G.

$$C = \left[V^{A^1}\ V^{A^2}\ V^{A^3}\ V^{A^4}\ V^{A^5}\ V^{A^6}\right][V^C]$$

$$F = \left[V^{A^7}\ V^{A^8}\ V^{A^9}\right][V^F]$$

$$G = [C\ \ F][V^G]$$

The matrix G can be reformulated in the form of relative ranking of respective elements to find solution *i*:

$$G_i = \frac{g_1}{g_1+g_2}\left[\frac{1}{\sum_{k=1}^{6} c_k}\right]\left[\begin{array}{l}\frac{a_i^1 c_1}{\sum_{k=1}^{9} a_k^1}+\frac{a_i^2 c_2}{\sum_{k=1}^{9} a_k^2}+ \\ \frac{a_i^3 c_3}{\sum_{k=1}^{9} a_k^3}+\frac{a_i^4 c_4}{\sum_{k=1}^{9} a_k^4}+ \\ \frac{a_i^5 c_5}{\sum_{k=1}^{9} a_k^5}+\frac{a_i^6 c_1}{\sum_{k=1}^{9} a_k^6}\end{array}\right]+$$

$$\frac{g_2}{g_1+g_2}\left[\frac{1}{\sum_{k=7}^{9} b_k}\right]\left[\frac{a_i^7 b_7}{\sum_{k=1}^{9} a_k^7}+\frac{a_i^8 b_8}{\sum_{k=1}^{9} a_k^8}+\frac{a_i^9 b_9}{\sum_{k=1}^{9} a_k^9}\right]$$

where, g_1 = ranking value of cost savings; g_2 = ranking value of future business relations;
c_1 to c_6 = ranking value of six subcriteria of cost savings;
b_7 to b_9 = ranking value of three subcriteria of future business relations;
$a_{network\ design}^{subcriteria} = a_1^1 \Rightarrow$ ranking value of Design 1 with respect to first cost saving subcriteria i.e. recycle.

The highest value in the solution vector refers to the most preferred network configuration. If $G_i > G_j$, we opt for alternative *i*.

4 Analysis

In this section, we apply the two methods explained in Section 3 to a company that is concerned with remanufacturing with facilities in Spain and Portugal [27]. The management board has requested a study on the facility location for a new product. They have proposed 5 different sites for the factory (Seville, Salemanca, Saragosa, Viseu and Madrid), 8 possible locations for warehouses and 5 potential locations for disassembly centres. For simplicity, there are 15 clusters of customers located in the same region. We also add 2 specialized or third party factories located in Zamora and Jean and 3 third party collection centres located in Palencia, Elda and Cordoba. The third party collection sites are assumed to be on the highway between different customer zones. The logic behind this is that placing it at the edge of the map is not appropriate for collecting goods due to long transportation routes. Total distance in miles is calculated as follows:

$$6371\times \mathrm{acos}(\cos\left(radians\left(90-latitude\,of\ A\right)\right)\times \cos\left(\begin{array}{l}radians\\ \left(90-latitude\,of\ B\right)\end{array}\right)+\sin\left(\begin{array}{l}radians\\ \left(90-latitude\ of\ A\right)\end{array}\right) \times\sin\left(\begin{array}{l}radians\\ \left(90-latitude\,of\ B\right)\end{array}\right)\times\cos\left(\begin{array}{l}radians\\ \left(\begin{array}{l}longitude\ of\ A-\\ logitude\,of\ B\end{array}\right)\end{array}\right))/1.609$$

The mixed integer program is modelled in AIMMS/CPLEX 12.5 [29] and the results of the deterministic approach in Table 4 show that the most preferred design based on cost optimization is collecting at the manufacturer's own store, inspecting and sorting in the warehouse and reprocessing in the original factory. The result of 6 extensive scenario analysis for each design based on high, medium and low level of demand and return from customer zones are presented in Table 5. If we have a flexible system, total costs will be lower compared to the deterministic and the scenario-based model. A flexible system is achieved by no minimum capacity requirement at each site (factory, warehouse and collection zone) and by excluding Constraints (5), (7), (9), (11) and (13). Table 4 and 5 present the comparison of the results based on total costs and number of assigned sites.

Table 4. Deterministic MIP result[1]

Network design	Model	#Fact-ory	#Ware-house	#Repro-cessing	#Inspe-ction	#Colle-ction	Fixed Costs	Transport Costs	Total Costs
Design 1	Det.[1]	5	6	5	5	15	813,000	548,137,350	548,950,350
	Det.[2]	3	6	5	6	15	829,000	281,126,745	281,955,745
Design 2	Det.[1]	5	6	2	5	15	813,000	618,958,700	619,771,700
	Det.[2]	3	6	1	5	15	699,000	311,803,770	312,502,770
Design 3	Det.[1]	5	6	5	3	15	563,000	572,124,600	572,687,600
	Det.[2]	3	6	4	5	15	579,000	291,133,120	291,712,120

[1] Det.[1]: both minimum and maximum constraints in the deterministic formulation, other things remaining same
Det.[2]: only maximum constraints in the deterministic formulation, other things remaining same

Design 4	Det.[1]	5	6	2	3	15	563,000	618,069,080	618,632,080
	Det.[2]	3	6	1	4	15	499,000	325,244,990	325,743,990
Design 5	Det.[1]	5	6	5	5	3	813,000	613,555,300	614,368,300
	Det.[2]	3	6	3	3	3	549,000	308,550,100	309,099,100
Design 6	Det.[1]	5	6	2	5	3	813,000	680,433,600	681,246,600
	Det.[2]	3	6	1	2	3	459,000	288,278,850	288,737,850
Design 7	Det.[1]	5	6	5	3	3	563,000	633,528,200	634,091,200
	Det.[2]	3	6	2	3	3	439,000	239,537,080	239,976,080
Design 8	Det.[1]	5	6	2	3	3	563,000	677,912,440	678,475,440
	Det.[2]	3	6	1	2	3	399,000	250,488,480	250,887,480

Table 5. Scenario analysis result[2]

Scenario 1: High 0.75; Medium 0.15; Low 0.10									
Network Design	**Model**	**#Factory**	**#Warehouse**	**#Reprocessing**	**#Inspection**	**#Collection**	**Fixed Costs**	**Transport Costs**	**Total Costs**
Design 1	*SceMod*[1]	5	6	5	5	15	813,000	548,137,350	548,950,350
	SceMod[2]	5	6	5	7	15	973,000	432,410,360	433,383,360
Design 2	*SceMod*[1]	5	6	2	5	15	813,000	618,958,700	619,771,700
	SceMod[2]	5	6	2	5	15	813,000	471,496,566	472,309,566
Design 3	*SceMod*[1]	5	6	5	3	15	563,000	572,124,600	572,687,600
	SceMod[2]	5	6	4	5	15	643,000	445,785,579	446,428,579
Design 4	*SceMod*[1]	5	6	2	3	15	563,000	618,069,080	618,632,080
	SceMod[2]	5	6	2	4	15	613,000	484,564,381	485,177,381
Design 5	*SceMod*[1]	5	6	5	5	3	813,000	613,555,300	614,368,300
	SceMod[2]	5	6	4	4	3	713,000	467,363,219	468,076,219
Design 6	*SceMod*[1]	5	6	2	5	3	813,000	680,433,600	681,246,600
	SceMod[2]	5	6	2	4	3	733,000	498,641,957	499,374,957
Design 7	*SceMod*[1]	5	6	5	3	3	563,000	633,528,200	634,091,200
	SceMod[2]	5	6	5	3	3	563,000	492,874,086	493,437,086
Design 8	*SceMod*[1]	5	6	2	3	3	563,000	677,912,440	678,475,440
	SceMod[2]	5	6	2	3	3	563,000	520,238,700	520,801,700
Scenario 2: High 0.15; Medium 0.10; Low 0.75									
Network Design	**Model**	**#Factory**	**#Warehouse**	**#Reprocess**	**#Inspection**	**#Collection**	**Fixed Costs**	**Transport Costs**	**Total Costs**
Design 1	*SceMod*[1]	5	6	5	5	15	813,000	548,137,350	548,950,350
	SceMod[2]	5	6	5	7	15	973,000	236,680,129	237,653,129
Design 2	*SceMod*[1]	5	6	2	5	15	813,000	618,958,700	619,771,700
	SceMod[2]	5	6	2	5	15	813,000	260,625,413	261,438,413
Design 3	*SceMod*[1]	5	6	5	3	15	563,000	572,124,600	572,687,600

[2] *SceMod*[1]: both maximum and minimum constraints in the scenario based model, other things remaining same
SceMod[2]: only maximum constraints in the scenario based model, other things remaining same

	SceMod²	5	6	4	5	15	643,000	242,661,264	243,304,264
Design 4	*SceMod¹*	5	6	2	3	15	563,000	618,069,080	618,632,080
	SceMod²	5	6	2	4	15	613,000	270,218,071	270,831,071
Design 5	*SceMod¹*	5	6	5	5	3	813,000	613,555,300	614,368,300
	SceMod²	5	6	4	4	3	713,000	257,023,053	257,736,053
Design 6	*SceMod¹*	5	6	2	5	3	813,000	680,433,600	681,246,600
	SceMod²	5	6	2	4	3	733,000	269,035,405	269,768,405
Design 7	*SceMod¹*	5	6	5	3	3	563,000	633,528,200	634,091,200
	SceMod²	5	6	5	3	3	563,000	271,505,075	272,068,075
Design 8	*SceMod¹*	5	6	2	3	3	563,000	677,912,440	678,475,440
	SceMod²	5	6	2	3	3	563,000	283,631,135	284,194,135
Scenario 3: High 0.10; Medium 0.15; Low 0.75									
Network Design	**Model**	**#Factory**	**#Warehouse**	**#Reprocess**	**#Inspection**	**#Collection**	**Fixed Costs**	**Transport Costs**	**Total Costs**
Design 1	*SceMod¹*	5	6	5	5	15	813,000	548,137,350	548,950,350
	SceMod²	5	6	4	6	15	873,000	226,003,893	226,876,893
Design 2	*SceMod¹*	5	6	2	5	15	813,000	618,958,700	619,771,700
	SceMod²	5	6	2	5	15	813,000	249,220,168	250,033,168
Design 3	*SceMod¹*	5	6	5	3	15	563,000	572,124,600	572,687,600
	SceMod²	5	6	4	5	15	643,000	231,625,964	232,268,964
Design 4	*SceMod¹*	5	6	2	3	15	563,000	618,069,080	618,632,080
	SceMod²	5	6	2	4	15	613,000	258,803,255	259,416,255
Design 5	*SceMod¹*	5	6	5	5	3	813,000	613,555,300	614,368,300
	SceMod²	5	6	4	4	3	713,000	245,674,875	246,387,875
Design 6	*SceMod¹*	5	6	2	5	3	813,000	680,433,600	681,246,600
	SceMod²	5	6	2	4	3	733,000	257,008,754	257,741,754
Design 7	*SceMod¹*	5	6	5	3	3	563,000	633,528,200	634,091,200
	SceMod²	5	6	5	3	3	563,000	259,843,015	260,406,015
Design 8	*SceMod¹*	5	6	2	3	3	563,000	677,912,440	678,475,440
	SceMod²	5	6	2	3	3	563,000	271,336,085	271,899,085
Scenario 4: High 0.15; Medium 0.75; Low 0.10									
Network Design	**Model**	**#Factory**	**#Warehouse**	**#Reprocess**	**#Inspection**	**#Collection**	**Fixed Costs**	**Transport Costs**	**Total Costs**
Design 1	*SceMod¹*	5	6	5	5	15	813,000	548,137,350	548,950,350
	SceMod²	5	6	5	7	15	973,000	303,177,956	304,150,956
Design 2	*SceMod¹*	5	6	2	5	15	813,000	618,958,700	619,771,700
	SceMod²	5	6	2	5	15	813,000	334,633,626	335,446,626
Design 3	*SceMod¹*	5	6	5	3	15	563,000	572,124,600	572,687,600
	SceMod²	5	6	4	5	15	643,000	313,361,985	314,004,985
Design 4	*SceMod¹*	5	6	2	3	15	563,000	618,069,080	618,632,080
	SceMod²	5	6	2	4	15	613,000	347,586,589	348,199,589

Design 5	$SceMod^1$	5	6	5	5	3	813,000	613,555,300	614,368,300
	$SceMod^2$	5	6	4	4	3	713,000	331,185,089	331,898,089
Design 6	$SceMod^1$	5	6	2	5	3	813,000	680,433,600	681,246,600
	$SceMod^2$	5	6	2	4	3	733,000	354,322,142	355,055,142
Design 7	$SceMod^1$	5	6	5	3	3	563,000	633,528,200	634,091,200
	$SceMod^2$	5	6	5	3	3	563,000	352,929,366	353,492,366
Design 8	$SceMod^1$	5	6	2	3	3	563,000	677,912,440	678,475,440
	$SceMod^2$	5	6	2	3	3	563,000	372,698,100	373,261,100
Scenario 5: High 0.10; Medium 0.75; Low 0.15									
Network Design	**Model**	**#Factory**	**#Warehouse**	**#Reprocess**	**#Inspection**	**#Collection**	**Fixed Costs**	**Transport Costs**	**Total Costs**
Design 1	$SceMod^1$	5	6	5	5	15	813,000	548,137,350	548,950,350
	$SceMod^2$	5	6	5	7	15	973,000	287,293,372	288,266,372
Design 2	$SceMod^1$	5	6	2	5	15	813,000	618,958,700	619,771,700
	$SceMod^2$	5	6	2	5	15	813,000	317,535,442	318,348,442
Design 3	$SceMod^1$	5	6	5	3	15	563,000	572,124,600	572,687,600
	$SceMod^2$	5	6	4	5	15	643,000	296,888,168	297,531,168
Design 4	$SceMod^1$	5	6	2	3	15	563,000	618,069,080	618,632,080
	$SceMod^2$	5	6	2	4	15	613,000	330,220,349	330,833,349
Design 5	$SceMod^1$	5	6	5	5	3	813,000	613,555,300	614,368,300
	$SceMod^2$	5	6	4	4	3	713,000	314,132,139	314,845,139
Design 6	$SceMod^1$	5	6	2	5	3	813,000	680,433,600	681,246,600
	$SceMod^2$	5	6	2	4	3	733,000	335,734,973	336,467,973
Design 7	$SceMod^1$	5	6	5	3	3	563,000	633,528,200	634,091,200
	$SceMod^2$	5	6	5	3	3	563,000	335,003,899	335,566,899
Design 8	$SceMod^1$	5	6	2	3	3	563,000	677,912,440	678,475,440
	$SceMod^2$	5	6	2	3	3	563,000	353,551,745	354,114,745
Scenario 6: High 0.75; Medium 0.10; Low 0.15									
Network Design	**Model**	**#Factory**	**#Warehouse**	**#Reprocess**	**#Inspection**	**#Collection**	**Fixed Costs**	**Transport Costs**	**Total Costs**
Design 1	$SceMod^1$	5	6	5	5	15	813,000	548,137,350	548,950,350
	$SceMod^2$	5	6	5	7	15	973,000	427,295,143	428,268,143
Design 2	$SceMod^1$	5	6	2	5	15	813,000	618,958,700	619,771,700
	$SceMod^2$	5	6	2	5	15	813,000	465,803,627	466,616,627
Design 3	$SceMod^1$	5	6	5	3	15	563,000	572,124,600	572,687,600
	$SceMod^2$	5	6	4	5	15	643,000	440,347,062	440,990,062
Design 4	$SceMod^1$	5	6	2	3	15	563,000	618,069,080	618,632,080
	$SceMod^2$	5	6	2	4	15	613,000	478,612,957	479,225,957
Design 5	$SceMod^1$	5	6	5	5	3	813,000	613,555,300	614,368,300
	$SceMod^2$	5	6	4	4	3	713,000	461,658,447	462,371,447
Design 6	$SceMod^1$	5	6	2	5	3	813,000	680,433,600	681,246,600

	SceMod[2]	5	6	2	4	3	733,000	492,081,439	492,814,439
Design 7	*SceMod*[1]	5	6	5	3	3	563,000	633,528,200	634,091,200
	SceMod[2]	5	6	5	3	3	563,000	486,610,679	487,173,679
Design 8	*SceMod*[1]	5	6	2	3	3	563,000	677,912,440	678,475,440
	SceMod[2]	5	6	2	3	3	563,000	513,387,395	513,950,395

The company wants to control the reverse logistics process and to protect the core product knowledge. Based on the case study review in Section 2, we assign ranking values for all the AHP elements (see Table 6). In view of selecting the optimal network design, we have synthesized the overall results in Figure 4. The AHP sensitivity analysis is illustrated in Figure 6 to 8 generated using Expert Choice [30]. The criteria - cost savings and future business relationships are shown by vertical bars and alternatives are displayed by horizontal lines in Figure 6. The intersection between horizontal and vertical lines shows the priority of the alternative for the given criterion (see right axis with label Alt%). The overall priority of each criterion is represented on the OVERALL line, while the priority of the objective function can be derived from the height of its bar at the left axis with label Obj%. The cost savings and future business relationship criteria are sensitive with respect to the goal of optimal network design (see Figure 7 and 8). After the intersection point between the solid vertical line and slanted line (see Figure 7), the priority of all network design with the recovery point as store of the manufacturer decreases and the priority of network design with third party collection center increases.

Figure 4. MS-W-F network solution

If we compare the solution of the mixed integer programming with AHP, it is evident that a manufacturer considers its own collection centre and factory for reprocessing but is reluctant to decide on inspection and sorting activities. The mixed integer programming opts for warehouses to do the inspection while AHP opts for the dedicated collection centre. But, if we closely observe the AHP result for selecting either the warehouse or a dedicated collection store for inspection, the difference is approximately 0.3%.

Table 6. Relative ranking of criteria

Criterion	Saaty Scale Ranking	Criterion	Saaty Scale Ranking
Recycle	1	Proprietary knowledge	6
Warehouse inspection	3	Customer interactions	1
Shipping scrap	7	Income and population density	9
Original factory reprocessing	9	Cost saving	1
Fixed costs	1	Future business relations	9
Tax structure	1		

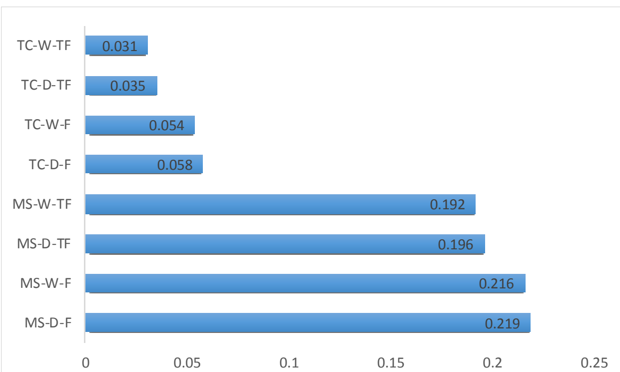

Figure 5. Analytic hierarchy process overall result

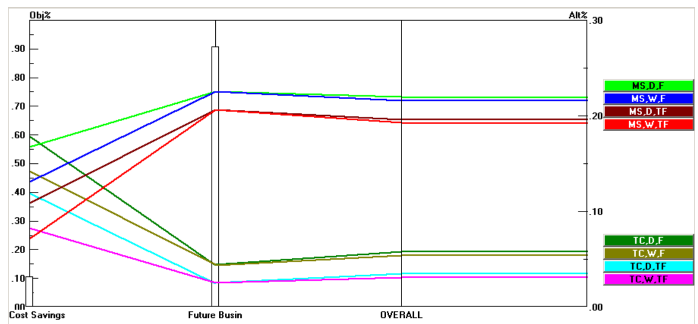

Figure 6. Performance sensitivity

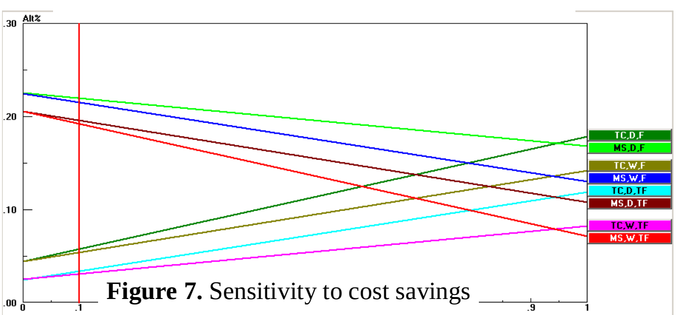

Figure 7. Sensitivity to cost savings

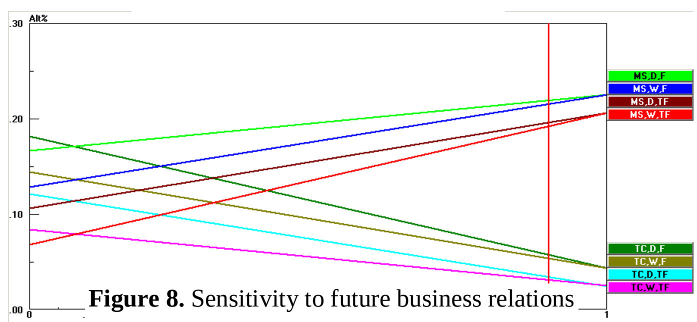

Figure 8. Sensitivity to future business relations

Therefore, the choice depends on the goal of the manufacturer, control the reverse system with inspection at the warehouse or reduce transportation costs with inspection at a dedicated collection center. However, both are feasible network designs for the company in the study.

5 Conclusion

The primary reason to use two different models (a mixed integer program and the analytic hierarchy process) for the same subject is to compare the solutions of both approaches and to test whether their results are the same. Analytic hierarchy process is based on ranking weights, assigned by the participant and quantified by developing the pairwise comparison matrix and the priority vector to generate the preferred solution. As the number of participants increases, the ranking may vary, leading to different solutions. It is not necessary that AHP's pairwise comparison matrix should be consistent. It is a trial and error method where the judgment must be reviewed until the inconsistency level is maximum 0.1. This method may not be suitable for large problems with multiple objectives. To overcome this limitation, we have used the mixed integer program model to generate a solution for each network design. Since the dataset in this research is rather small size, it is important to recognize that the computational time will grow with the problem size. It is necessary to include a decomposition method (e.g. benders decomposition) if we want to model large networks with multiple products and multiple manufacturers. By using scenario dependent demand and return parameters, uncertainty is incorporated into the deterministic model.

Further research should focus on a detailed stochastic modeling approach to incorporate the uncertainty of reverse logistics systems. From a practical point of view, our mixed integer programming model focuses on selecting only one network configuration, which might not be the case in a real world system. Different network models may exist for different recovery options such as CopyMagic case study by Thierry et al. [14] or the same model may apply to different recovery options such as IBM case study by Fleischmann [1]. The future research should work on single mixed integer programming model that generates for each recovery option a configuration for large scale networks with multiple products and multiple manufacturers.

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