Computers & Industrial Engineering xxx (2008) xxx–xxx

Contents lists available at ScienceDirect

Computers & Industrial Engineering

journal homepage: www.elsevier.com/locate/caie

Strategic network design for reverse logistics and remanufacturing using new and old product modules

Akshay Mutha *, Shaligram Pokharel

Center for Supply Chain Management, School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639 798, Singapore

ARTICLE INFO

Article history:
Received 1 August 2007
Received in revised form 15 January 2008
Accepted 10 June 2008
Available online xxxx

Keywords:
Reverse logistics
Network design
Product modularity
Cost
Remanufacturing

ABSTRACT

Establishment of reverse logistics (RL) networks for various original equipment manufacturers (OEM's) is gaining significant importance. Various green legislations are forcing OEMs to take back their used, end-of-lease or end-of-life products, or products under warranty to minimize wastes and conserve resources. Therefore OEMs have turned to a better design of their products for maximum reuse and recycling and to retrieve back the used products through a network for reuse, remanufacture, recycle or disposal, so that maximum value can be achieved from their used products. However, designing of network points and assigning capacities to them depend not only on the volume of returned products but also on the demand for remanufactured products and the parts of used products. If OEMs are not able to add value to the used product, there would be no incentive to design a complex network.

In this paper, a mathematical model for the design of a RL network is proposed. It is assumed that the returned products need to be consolidated in the warehouse before they are sent to reprocessing centres for inspection and dismantling. Dismantled parts are sent for remanufacturing or to the secondary market as spare parts. Recycling and disposal of these modules are also considered in the model. The use of the model is shown through its application in a numerical example.

1. Introduction

Implementation of legislation, social responsibility, corporate imaging, environmental concern, economic benefits and customer awareness are forcing OEMs not only to provide more environmentally friendly products but also to take back used products at its end of life. Products can also be returned for reasons such as customer dissatisfaction and warranty (Rogers & Tibben-Lembke, 1999; Tibben-Lembke, 2002). Such products can be sorted for reuse, remanufacture, recycle and disposal. Reuse of used products by some value addition is not a new concept. Also, industries are using remanufacturing for expensive products such as turbines used in airplane and electricity generation systems. In these cases recovery of used products is economically more attractive than disposal (Koh, Hwang, Sohn, & Ko, 2002). OEMs are incorporating 'extended producer responsibility' (EPR) to reduce wastes in a used product (Carter & Ellram, 1998). While on the other hand, they are implementing networks to take back their products through various channels. However, if returned products are not handled efficiently then OEMs would incur larger costs that can increase the cost of the new product. Therefore, network for return of products should be efficient and cost effective.

On the design part, OEMs are increasingly modularizing their products (Fredrikson, 2006) not only to reduce the steps for final assembly but also to facilitate faster dismantling and repair of used products (Ulrich & Tung, 1991). Therefore, modularization helps to avoid disposal of usable modules retrieved from the used products (Dowlatshahi, 2000). Also, OEMs are substituting certain parts and materials by recyclable and environment friendly alternatives (Gupta & Isaacs, 1997).

In this paper, a mathematical model is proposed for the design of a RL network handling product returns. The model considers the supply of returned products through third party collectors. It considers storing, reprocessing, remanufacturing facilities and new module suppliers in the network. If the recovered modules are not sufficient to remanufacture the products to meet the demand, then certain quantities of certain new modules need to be purchased. We also consider demand for used modules in the secondary markets. The design of such a network is strategic as it involves a decision on the number, location and capacities of various facilities and allocation of material flows between them (Dethloff, 2001; Dowlatshahi, 2005; Jayaraman, Guide, & Srivastava, 1999; Lu & Bostel, 2007; Realff, Ammons, & Newton, 2000) and is one of the most challenging elements of managing RL operations (Pochampally & Gupta, 2005). A prop-

* Corresponding author.
E-mail addresses: muth0007@ntu.edu.sg (A. Mutha), Shaligram@pmail.ntu.edu.sg (S. Pokharel).

0360-8352/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.cie.2008.06.006

erly designed network can also enhance dealing with remanufacturing activities (Prahinski & Kocabasoglu, 2006) and competitive advantage (Gungor & Gupta, 1999).

2. Research on design of RL network

Several researchers have studied the design of RL network focusing on their cost effectiveness. Studies have concluded that for recycling of the returned products, logistics costs account for a large share of the total costs (Beullens, 2004; Jahre, 1995; Stock, 1992). RL requires high investment and a high portion of logistics costs (Nagel & Meyer, 1999). The RL cost can vary from 4% (Rogers, 2001) to 9.49% (Daugherty, Autry, & Ellinger, 2001) of the total logistics cost. In the retail and manufacturing sectors, it is estimated that RL accounts for about 5–6% of the total logistics cost (Raimer, 1997). Transportation of used products is the most challenging issue in RL (Fleischmann, 2001; Krumwiede & Sheu, 2002) as smaller return quantities and variability in product types increase the transportation costs (Ferrer & Whybark, 2000; Tibben-Lembke & Rogers, 2002). Biehl, Prater, and Realff (2007) emphasize on the need for collection centres in a reverse production system to help in maximizing collection of returned products. Reimer, Sodhi, and Jayaraman (2006) have developed truck sizing models for collection of wastes and transporting them to recovery centres. Murphy (1986) stated that private warehousing was popular for RL because of its convenience and reliability. Min, Ko, and Ko (2006b) have developed a mixed integer non-linear programming model to determine the exact length of holding time for spatial and temporal consolidation at the initial collection points to minimize the total RL costs.

A review on various quantitative models for RL networks is given by Fleischmann et al. (1997). The location of collection points in a RL system has been examined by Bloemhof-Ruwaard, Fleischmann, and van Nunen (1999). Fleischmann, Beullens, Bloemhof-Ruwaard, and van Wassenhove (2001) have presented a generic MILP model considering a single product flow between incapacitated facilities and reprocessing as a product-recovery option. Jayaraman, Patterson, and Rolland (2003) have proposed a MILP model by considering the reverse flow of goods. Pochampally, Gupta, and Kamarthi (2004) have proposed a physical programming approach to identify potential recovery facilities in a region where reverse supply chain is to be established. Savaskan, Bhattacharya, and van Wassenhove (2004) have proposed a product-recovery strategy depending on who collects the used products namely the manufacturer; the retailer; or a designated third party. The findings suggest that optimal results are achieved when the retailer collects the returned products. However, the authors consider the flow of goods in only a two echelon system i.e. retailer and manufacturer. De Koster, de Brito, and van de Vendel (2002) have investigated the factors contributing to RL network decisions by considering inbound and outbound flows, the transport routes, the return volume, choice of receiving warehouse and the market location for returned products. The authors recommend that retailers that supply to stores should collect the returned material to the distribution centre using the same truck which delivered the products. Also, retailers that handle a high volume of returns should unload and sort returns in a separate area in the distribution centre. Beamon and Fernandes (2004) have developed an integer programming model for a four echelon reverse supply chain by assuming infinite storage capacities and same holding costs for recovered and new products. The authors assume that the remanufactured products are of the same quality as that of the new products. Therefore remanufactured products can be sold in the same condition as new ones to meet the market demand. Kusumastuti, Piplani, and Lim (2004) have presented a multi-objective and multi-period MILP model for RL network design for modularized products. The model determines the number of existing forward flow facilities to be used and the number of dedicated facilities to be setup for handling return flows. The authors have not considered the use of new modules in remanufactured products. Salema, Povoa, and Novais (2007) have proposed a MILP model to analyze the problem of closed loop supply chains. They consider multi-product returns with uncertain behaviour but limit their consideration of demand for returned products to factories and not to secondary markets or spare markets. Thus a supplier network which may be required to remanufacture a new product to meet the market demand is not considered. Also, this model is not suitable for modular products. Lu and Bostel (2007) have also developed an incapacitated model for RL.

Pohlen and Farris (1992) have investigated the reverse distribution channel structure in plastics recycling and analyzed the compaction and routing issues related to transportation in the RL process. Spengler, Puchert, Penkuhn, and Rentz (1997) have developed a model based on linear activity analysis to determine locations and capacities of recycling facilities for reprocessing by-products of steel industries. Barros, Dekker, and Scholten (1998) have proposed a logistics network for recycling of polluted sand by using MILP to determine the optimum number, capacities, and locations of the depots and cleaning facilities in the network. Louwers, Kip, Peters, Souren, and Flapper (1999) have proposed a RL network model to determine appropriate locations and capacities for collection, preprocessing and redistribution facilities of carpet wastes. Realff, Ammons, and Newton (2004) have proposed a multi-period MILP model for carpet recycling. Their model analyzes a set of alternative scenarios identified by the decision maker and provides a near optimal solution for network design. Schultmann, Zumkeller, and Rentz (2006) have developed a recycling network for the German automotive industry by minimizing the travel routes between dismantling centres and reprocessing facilities. The authors solve their network model by using linear programming and meta-heuristics methods. Wojanowski, Verter, and Boyaci (2007) have developed a stochastic model to analyze the network structure for product returns under a refundable-deposit scheme. They show that the success of the profitability of the network depends on the accessibility of the customers to the collection centres. Zhou, Naim, and Wang (2007) analyzed the battery recycling practices in China and identified its obstacles and weaknesses. They recommend legislative actions, technical guidance and administrative resources, and cost-effective recycling and RL infrastructure to improve the system.

Kroon and Vrijens (1995) have considered the design of a logistics system for used plastic containers. They propose a MILP model to determine the number of containers required to run a five echelon system under consideration, the appropriate service, and distribution and collection fee per shipment for empty containers and location of depots for empty containers. Berger and Debaillie (1997) have proposed a model for extending a production/distribution network with disassembly centres to allow the recovery of used products. The authors consider each plant and distribution centres with fixed locations and capacities, but determine the location and capacity of the disassembly centres based on a multi-level capacitated MILP model. Jayaraman et al. (1999) have also proposed a model for location of remanufacturing and distribution facilities by optimizing the quantities for remanufacturing, transshipment and stocking. Pati, Vrat, and Kumar (2006) have formulated a mixed integer goal programming model for analyzing paper recycling network. The model assumes five echelons and studies the inter-relationship between cost reduction, product quality improvement through increased segregation at the source, and environmental benefits through waste paper recovery. The model also assists in determining the facility location, and route and flow of different varieties of recyclable wastes.

Shih (2001) have proposed a MILP model to determine the optimal collection and recycling system for end-of-life computers and home appliances. The model helps to determine the location for storage and treatment facilities. Walther and Spengler (2005) have developed a model for the treatment of electrical and electronic wastes in Germany. This model optimizes the allocation of discarded products, disassembly activities and disassembly fractions to participants of the treatment system. Ravi, Ravi, and Tiwari (2005) presented an ANP based decision model to analyze the options in RL for end-of-life computers and link them to the determinants, dimensions and enablers of RL. Kara, Rugrungruang, and Kaebernick (2007) have modeled the collection of end-of-life electrical appliances with high degree of uncertainty in quality and quantity of the returned products. The authors suggest that low costs can be achieved when local councils act as collectors.

Fernandez and Kekale (2005) have studied the implications of modular product architecture on RL strategies. They discuss that modular structure of a product affects the decision making in terms of destination for returned products or its modules. Krikke, van Harten, and Schuur (1999a) analyzed a RL network for photocopiers with a fixed supplying processes and disassembly. The authors propose a MILP model to determine optimal locations for the preparation and reassembly operations. The modular nature of computer monitors is considered in RL by Krikke, van Harten, and Schuur (1999b) to find a profit-optimal product recovery and disposal strategy for each of the six types of monitors considered in the study. Their strategy includes options of partial disassembly, mixed and separate recycling. Franke, Basdere, Ciupek, and Seliger (2006) have developed an optimization model for planning of capacities and production programs for remanufacturing of mobile phones. Their model considers modular nature of the product and considers reuse; component retrieval; material recycling; and disposal as the four possible options for recovery of products or its modules. The authors have also included an external procurement activity (suppliers) to satisfy the market demand. The process capacities and the remanufacturing program are determined by the optimization model. They have developed a simulation model to help in determining the required transport and storage capacities, and the performance of the remanufacturing system. Kim, Song, Kim, and Jeong (2006) discussed the aspect of supply planning in RL considering modular structure of products and address the problem of scheduling supplies of new modules from suppliers to meet the demand after a certain recovery of modules from the returned products. The authors present a MILP model for maximizing the cost savings by optimally deciding which quantity of products/modules are to be refurbished and which are to be outsourced from the suppliers.

Min, Ko, and Ko (2006a) have proposed a single objective, nonlinear, mixed integer programming model to provide a minimum cost solution for network design of product-recovery systems. Their proposed model considers trade-offs between freight rate discounts and inventory cost savings due to consolidation and transshipment. The authors perform sensitivity analysis on the holding period to determine the optimal length of holding time for consolidation and the collection centres. The model indicates that as the maximum holding period increases the RL costs decreases, but the overall network structure remains stable. The authors noticed dramatic cost saving in total RL costs after setting the maximum holding period at three days.

Research is also done in areas of product disassembly planning (Guide, Jayaraman, & Srivastava, 1999; Gungor & Gupta, 1998; Lambert, 2002; Mok, Kim, & Moon, 1998), vehicle routing and planning in reverse logistics (Alshamrani, Mathur, & Ballou, 2007; Dethloff, 2001) and the pricing of a "remanufactured" product (Heese, Cattani, Ferrer, Gilland, & Roth, 2005). Teunter, Van der Laan, and Inderfurth (2000) have compared the performances of different methods for setting the holding cost rates in average cost inventory models with reverse logistics and Hwang, Oh, and Gen (2005) have proposed a model for inventory control in recycling.

2.1. Summary of literature review

The above review shows that the design of RL network is an important research problem as the circumstances leading to the model development could be unique. The research emphasizes on the reduction of RL costs through the choice of locations and capacities. The research also shows that remanufacturing of products and their sale in secondary markets are important considerations being studied for different types of returned products. While some researchers have focused mainly of used products only, others have recognized that used products do contain modules with different qualities. Kusumastuti et al. (2004) and Franke et al. (2006) have considered modular architecture of the returned products for remanufacturing operations. While Franke et al. (2006) have considered new module suppliers for the remanufacturing of new products; Kusumastuti et al. (2004) have considered multi-product configurations of returned products.

In this paper, we present a model for handling product returns. The model considers modular product structure with different disposal and recycling fractions for each module of each product. The model is also suitable for multi-product configurations. The focus is on modular product structure in a RL network that not only supplies quality used modules for remanufacturing but also to the spare markets. The mismatch of modules for remanufacturing is assumed to be tackled by purchasing through pre-qualified suppliers. The model considers disposal as one of the options to be exercised by OEMs. Therefore the model is expected to represent a more realistic RL situation. It is assumed that a larger price and quality differentials between the new and remanufactured product can create demand for the remanufactured product. However this factor is not considered explicitly in the model. It is assumed that the spare parts, if any, can fetch a higher unit value compared to the remanufactured products. Also, if the number of modules are in excess of demand, they are either recycled (incurring transport costs) or stored in the reprocessing centres (incurring inventory holding costs) till further demand is received. This enables economic decision making on recycling of excess quantities. The focus here is on deciding the number of facilities, their locations and allocation of corresponding flow of used products and modules at an optimal cost for a given market demand and used product returned quantities. Although, the demands for remanufactured products, spare markets can vary, this current model assumes only deterministic demands by assuming historical averages.

3. Model formulation

A generic network diagram used for the analysis is given in Fig. 1. It involves nine echelons. As suggested by Biehl et al. (2007), the model assumes retailers as collecting points a well. The other echelons considered in the model are warehouses (for storage and consolidation), reprocessing centres for inspection and dismantling, remanufacturing factories, recycling centres, disposal sites and markets for spare parts and remanufactured products. The network considers pre-selected new module suppliers as a separate echelon. Other assumptions are as follows:

1. An infinite source of used products is assumed.

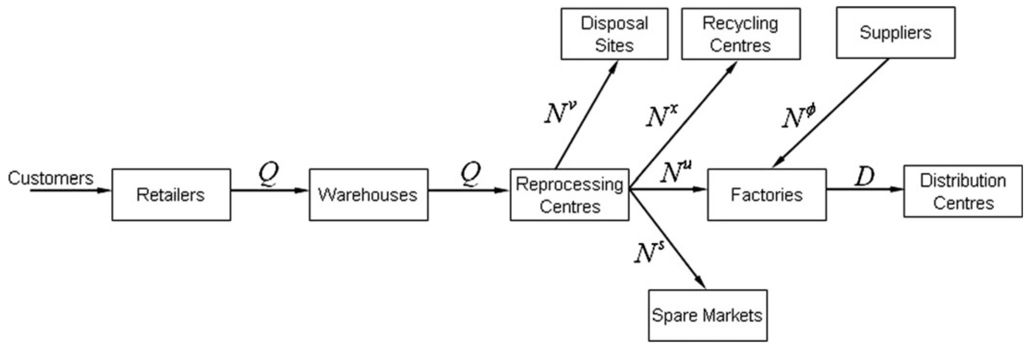

Fig. 1. Proposed RL structure.

2. Customers provide their used products to pre-specified retailers. The goods collected in each retailer are transported to the warehouses as soon as possible so that they do not incur any holding costs.
3. The warehouse acts as a storage and consolidation centre and the cost for consolidation is assumed insignificant to its holding cost (Dowlatshahi, 2000; Krikke, Pappis, Tsoulfas, & Bloemhof-Ruwaard, 2001; Lee & Dong, 2007; Shih, 2001).
4. The dismantling operations are carried out in the RPC, where the modules are disassembled, cleaned, tested and sorted for reuse, remanufacture, spare and recycle. As a preference, spare market demands are met due to high value that it fetches from selling spare parts. Reuse of products is not considered as they can be sold in the secondary markets by the retailers directly.
5. The warehouse, the RPC and the factory are considered to have a monthly fixed cost irrespective of the usage. Also, they incur different inventory holding costs.
6. All the returned products are not suitable for remanufacturing. Therefore some new modules may be required for remanufacturing of the products. The final assembly of the product with used and new modules, if any, is done inside the factory. The factory has inventory holding costs only for the used modules while it operates on Just-In-Time (JIT) delivery of new modules.
7. Transport cost is calculated with respect to the distance and overhead costs assuming full truck loads (Bowersox & Closs, 1996; Louwers et al., 1999; Shih, 2001).
8. It is assumed that remanufactured products are not held at the factory but are transported to distribution centres immediately after production (Du & Evans, 2008).
9. If the number of modules are in excess of demand, then they are either recycled (incurring transport costs) or stored in the RPC (incurring inventory holding costs) till further demand is received.

Customers (for remanufactured products) are represented by demands at the distribution centre. We have considered the return of product having a unique modular structure that is the module usage rate is 1. The notations and description for model parameters are given in Table 1 where as the description on decision variables are given in Table 2. The mathematical formulation for the proposed model is detailed below.

3.1. Balance equations

Total quantity of returned product ‘p’ be Q, which is given as

$$Q = \sum_{p=1}^{P} Q_p \tag{1}$$

Table 1
Symbols used in model formulation – parameters

Notation	Description
r	Set of retailers in the network, $r = 1,2,3,\ldots,R$
w	Set of warehouses in the network, $w = 1,2,3,\ldots,W$
j	Set of reprocessing centres (RPC's) in the network, $j = 1,2,3,\ldots,J$
s	Set of markets for spare products, $s = 1,2,3,\ldots,S$
u	Set of assembling factories in the network, $u = 1,2,3,\ldots,U$
v	Set of possible disposal sites, $v = 1,2,3,\ldots,V$
x	Set of possible recycling centres, $x = 1,2,3,\ldots,X$
z	Set of new module suppliers for product p, $z = 1,2,3,\ldots,Z$
h	Set of distribution centres (DC's) which serve as secondary markets, $h = 1,2,3,\ldots,H$
C_{pi_w}	Inventory carrying cost/product/time at warehouse w
C_{pi_j}	Inventory carrying cost/product/time at RPC j
C_{in_pj}	Inventory carrying cost/module/time at RPC j
C_{in_pu}	Inventory carrying cost/module/time at factory u
C_p	Unit cost of returned product ‘p’
C_{n_pz}	Unit cost of module ‘n’ of product ‘p’ from supplier z
C_{pA_u}	Assembly cost/product ‘p’ for factory u
$C_{d_{n_p}v}$	Unit disposal fees for module ‘n’ of product ‘p’ at site v
$C_{R_{n_p}j}$	Unit reprocessing cost for module ‘n’ of product ‘p’ at RPC j
C_u	Fixed cost of factory u
C_w	Fixed cost of warehouse w
C_j	Fixed cost of RPC j
T_p	Transport cost/product ‘p’ (for a given distance)
T_{n_p}	Transport cost/module n of product ‘p’ (for a given distance)
T_{pfg}	Transport cost/finished product ‘p’ (for a given distance)
V_{n_p}	Unit volume of module n of product ‘p’
V_p	Unit volume of product ‘p’
D	Total demand for all products at all distribution centres
D_{h_p}	Demand for product ‘p’ at distribution centre h
D_s	Demand at spare market s
D_u	Demand of factory u
D_x	Capacity of recycling centre x
D_v	Capacity of disposal site v
σ_{n_p}	Disposal fraction of module n of product p
ρ_{n_p}	Recyclability fraction of module n of product p
D_w	Storage capacity of warehouse w
D_j	Storage capacity of RPC j
D_{Rej}	Processing capacity of RPC j

and $Q_p = \sum_{r=1}^{R} Q_{p_r}, \quad \forall p$

Each product ‘p’ is made up of modules ‘n’. The total number of modules is given as

$$Q_p = \sum_{n=1}^{N} M_{n_p}, \quad \forall p \tag{2}$$

Also, total quantity of product ‘p’ can be written as

Table 2
Symbols used in model formulation – decision variables

Notation	Description
Q	Total quantity of products returned by the customers
Q_p	Quantity of product '*p*' returned by the customers
Q_{r_p}	Quantity of product '*p*' with retailer *r*
Q_{w_p}	Quantity of product '*p*' with warehouse *w*
Q_{j_p}	Quantity of product '*p*' with RPC *j*
N^s	Quantity of module '*n*' of product '*p*' sent to spare market
N^u	Quantity of module '*n*' of product '*p*' sent to factory
N^x	Quantity of module '*n*' of product '*p*' sent for recycling
N^I	Quantity of module '*n*' of product '*p*' stored at RPC for future demand
N^v	Quantity of module '*n*' of product '*p*' to be disposed
N^B	Balance quantity of module '*n*' of product '*p*' available for manufacturing or storing
M_{n_p}	Quantity of returned module '*n*' of product '*p*'
N^ϕ	Quantity of new module '*n*' of product '*p*' ordered

$$Q_p = \frac{\sum_{n=1}^{N} M_{n_p}}{\sum_{n=1}^{N} n_p}, \quad \forall p \tag{3}$$

Total products (in modular form) collected at all retailers R is given as

$$Q_{r_p} = \sum_{n=1}^{N}\sum_{r=1}^{R} M_{n_p r}, \quad \forall p \tag{4}$$

Total products consolidated at all warehouses W is given as

$$Q_{w_p} = \sum_{n=1}^{N}\sum_{w=1}^{W} M_{n_p w}, \quad \forall p \tag{5}$$

The balance of products between the retailers and the warehouses is given as

$$\sum_{n=1}^{N}\sum_{r=1}^{R} M_{n_p r} = \sum_{n=1}^{N}\sum_{w=1}^{W} M_{n_p w}, \quad \forall p \tag{6}$$

Total products transported to all RPC's J for reprocessing is given as

$$Q_{j_p} = \sum_{n=1}^{N}\sum_{j=1}^{J} M_{n_p j}, \quad \forall p \tag{7}$$

The balance of products between the retailers, warehouses and RPC's is given as

$$\sum_{n=1}^{N}\sum_{r=1}^{R} M_{n_p r} = \sum_{n=1}^{N}\sum_{w=1}^{W} M_{n_p w} = \sum_{n=1}^{N}\sum_{j=1}^{J} M_{n_p j}, \quad \forall p \tag{8}$$

In the RPC, the products are dismantled to modules and certain pre-specified modules of each type of product are disposed as per their disposal fraction. The quantity of modules disposed at disposal sites V is given as

$$\sum_{n \in N^v} M_{n_p} = \sum_{n \in N^v}\sum_{v=1}^{V}\sum_{j=1}^{J} \sigma_{n_p} M_{n_p j v}, \quad \forall p, \ \forall n, \ N^v \in N \tag{9}$$

Similarly, modules which are not good for remanufacturing or sale, but are recyclable are sent for recycling. Certain pre-specified modules of each type of product are recycled as per their recyclability fraction. The quantity of modules sent for recycling at recycling sites X is given as

$$\sum_{n \in N^x} M_{n_p} = \sum_{n \in N^x}\sum_{x=1}^{X}\sum_{j=1}^{J} \rho_{n_p} M_{n_p j x}, \quad \forall p, \ \forall n, \ N^x \in N \notin N^v \tag{10}$$

The above two options could create a mismatch of the balance modules in the RPC. Thus, of the balance modules, the demand for the spare markets (D_s) and remanufacturing factories (D_u) is catered in that preference. This is based on the logic that parts can fetch higher revenues to the OEMs.

The demand for modules in the spare markets S is given as

$$\sum_{n \in N^s} D_{n_p s} \leqslant \sum_{n=1}^{N}\sum_{j=1}^{J} M_{n_p j} - \sum_{n \in N^v} M_{n_p} - \sum_{n \in N^x} M_{n_p}, \quad \forall p, \ \forall n, \ \forall s, \quad N^s \in N \notin N^v \notin N^x \tag{11}$$

If 10 unique modules ($m = 1, 2, 3, \ldots, 10$) are returned to the RPC, of which module 1 and 2 are disposed and module 3, 4 and 5 are sent for recycling, the balance modules 6, 7, 8, 9 and 10 can be used to cater to the demand of spare markets and remanufacturing factories. Thus, if modules 6, 7 and 8 are sent to the spare market, only modules 9 and 10 will be left behind in the RPC. Now, if the demand at the remanufacturing factory is $\geqslant 1$, the modules 9 and 10 can be sent to cater the demand. Else, they will be stored in the RPC till the next period.

Thus, the balance of modules, available for remanufacturing or storing is given as

$$\sum_{n \in N^B}\sum_{j=1}^{J} M_{n_p b_j} = \sum_{n=1}^{N}\sum_{j=1}^{J} M_{n_p j} - \sum_{n \in N^v} M_{n_p} - \sum_{n \in N^x} M_{n_p} - \sum_{n \in N^s}\sum_{s=1}^{S} D_{n_p s}, \quad \forall p, \ \forall n, \ N^B \in N \notin N^v \notin N^x \notin N^s \tag{12}$$

The number of reprocessed modules sent to the factories is given by

$$\sum_{n \in N^u} M_{n_p u} \geqslant D_u, \quad \forall p, \ \forall n, \ \forall u, \ N^u \in N^B \notin N^v \notin N^x \notin N^s \tag{13}$$

Thus, of the balance quantity of modules (Eq. (12)), the quantity of modules stored in the RPC is given as

$$\sum_{n \in N^I}\sum_{j=1}^{J} M_{n_p j} = \sum_{n \in N^B}\sum_{j=1}^{J} M_{n_p b_j} - \sum_{n \in N^u}\sum_{u=1}^{U} M_{n_p u}, \quad \forall p, \ \forall n, \ N^I \in N^B \notin N^v \notin N^x \notin N^s \tag{14}$$

Now the demand of the remanufacturing factories can be met by the modules supplied by the RPC and by the modules procured from the new module suppliers. When the demand at the remanufacturing factories is less than the balance modules in the RPC, the required modules are supplied while the rest are stored. When the demand is higher than the quantity of modules supplied by the RPC, the factories need to procure the balance modules (for each product) from the new module suppliers. Thus, the balance quantity required to be procured from the new module suppliers Z is given by

$$\phi = D_u - N^u, \quad \forall p, \ \forall n, \ \forall u \tag{15}$$

Thus, the total quantity of modules required by the remanufacturing factories to meet the market demand is the sum of the modules supplied by the RPC and those procured from the new module suppliers and is given as

$$\sum_{n=1}^{N} D_{n_p h} = \sum_{n \in N^u}\sum_{u=1}^{U} M_{n_p u} + \sum_{n \in N^\phi}\sum_{z=1}^{Z} M_{n_p z}, \quad \forall p, \ \forall n, \ \forall h \tag{16}$$

This demand can be given in terms of products as

$$D_{h_p} = \frac{\sum_{n=1}^{N}\sum_{h=1}^{H} M_{n_p h}}{\sum_{n=1}^{N} n_p}, \quad \forall p \tag{17}$$

3.2. Costs associated with reverse logistics

Various costs associated with the network are as follows.

Please cite this article in press as: Mutha, A., & Pokharel, S., Strategic network design for reverse logistics and remanufacturing using new ..., *Computers & Industrial Engineering* (2008), doi:10.1016/j.cie.2008.06.006

3.2.1. Transport costs

This is the cost paid for transporting various products/modules from one location to another. The total transportation cost includes the total cost paid for transporting product between different supply chain echelons as given below.

The cost of transporting product ‘*p*’ between retailer ‘*r*’ and warehouse ‘*w*’ is as

$$\sum_{w=1}^{W}\sum_{r=1}^{R} Q_{p_r} T_{p_{rw}}, \quad \forall p \tag{18}$$

The cost of transporting product ‘*p*’ between warehouse ‘*w*’ and RPC ‘*j*’ is as

$$\sum_{j=1}^{J}\sum_{w=1}^{W} Q_{p_w} T_{p_{wj}}, \quad \forall p \tag{19}$$

The cost of transporting modules between RPC ‘*j*’ and spare market‘*s*’ is as

$$\sum_{n\in N^s}\sum_{j=1}^{J}\sum_{s=1}^{S} D_{n_p s} T_{n_p js}, \quad \forall p,\ \forall n \tag{20}$$

The cost of transporting modules between RPC ‘*j*’ and factory ‘*u*’ is as

$$\sum_{n\in N^u}\sum_{j=1}^{J}\sum_{u=1}^{U} M_{n_p u} T_{n_p ju}, \quad \forall p,\ \forall n \tag{21}$$

The cost of transporting modules between RPC ‘*j*’ and recycling site ‘*x*’ is as

$$\sum_{n\in N^x}\sum_{j=1}^{J}\sum_{x=1}^{X} M_{n_p} T_{n_p jx}, \quad \forall p,\ \forall n \tag{22}$$

The cost of transporting modules between RPC ‘*j*’ and disposal site ‘*v*’ is as

$$\sum_{n\in N^v}\sum_{j=1}^{J}\sum_{v=1}^{V} M_{n_p} T_{n_p jv}, \quad \forall p,\ \forall n \tag{23}$$

The cost of transporting remanufactured finished goods between factory ‘*u*’ and DC ‘*h*’ is as

$$\sum_{h=1}^{H}\sum_{u=1}^{U} D_{h_p} T_{pfg_{uh}}, \quad \forall p \tag{24}$$

3.2.2. Inventory costs

Inventory costs at each facility could vary depending on the quantity of each product/module. The cost for acquiring Q_p quantity of product ‘*p*’ from the customers is written as

$$\sum_{p=1}^{P} Q_p C_p, \quad \forall p \tag{25}$$

The inventory cost of product ‘*p*’ at warehouse ‘*w*’ is given as

$$\sum_{w=1}^{W} Q_{w_p} C_{pi_w}, \quad \forall p \tag{26}$$

The inventory cost of product ‘*p*’ at RPC ‘*j*’ is given as

$$\sum_{j=1}^{J} Q_{j_p} C_{pi_j}, \quad \forall p \tag{27}$$

The inventory cost of module ‘*n*’ of returned product ‘*p*’ at RPC ‘*j*’ is given as

$$\sum_{n\in N^J}\sum_{j=1}^{J} M_{n_p j} C_{in_p j}, \quad \forall p,\ \forall n \tag{28}$$

The inventory cost of module ‘*n*’ of returned product ‘*p*’ at factory ‘*u*’ is given as

$$\sum_{n\in N^u}\sum_{u=1}^{U} M_{n_p u} C_{in_p u}, \quad \forall p,\ \forall n \tag{29}$$

3.2.3. Fixed costs

Since we assume that the warehouse, the RPC and the factory are rented, these facilities incur fixed monthly charges. The total fixed cost for each facility is given as

$$\sum_{w=1}^{W} C_w - \text{fixed cost of warehouse ‘}w\text{’} \tag{30}$$

$$\sum_{j=1}^{J} C_j - \text{fixed cost of RPC ‘}j\text{’} \tag{31}$$

$$\sum_{u=1}^{U} C_u - \text{fixed cost of factory ‘}u\text{’} \tag{32}$$

3.2.4. New module costs

It is virtually impossible to reuse all the components/modules of a returned product. Hence, in order to meet the market demand, companies may require procuring new modules to produce ‘as good as new’ products. This quantity N^{ϕ} is dependent on the market demand ‘*D*’. This cost is as

$$\sum_{n\in N^{\phi}}\sum_{z=1}^{Z} M_{n_p z} C_{n_p z}, \quad \forall p,\ \forall n \tag{33}$$

3.2.5. Reprocessing costs

This is the cost incurred in reprocessing the module ‘*n*’ of returned product ‘*p*’ at RPC ‘*j*’. This includes,

cost for reprocessing the quantity of modules of product ‘*p*’ for spare market ‘*s*’,

$$\sum_{n\in N^s}\sum_{j=1}^{J}\sum_{s=1}^{S} M_{n_p s} C_{R_{n_p} j}, \quad \forall p,\ \forall n \tag{34}$$

and cost for reprocessing the quantity of modules of product ‘*p*’ for factory ‘*u*’,

$$\sum_{n\in N^u}\sum_{j=1}^{J}\sum_{u=1}^{U} M_{n_p u} C_{R_{n_p} j}, \quad \forall p,\ \forall n \tag{35}$$

3.2.6. Disposal costs

This is the cost incurred in disposing the modules at site ‘*v*’. They are mainly dependant on the legislative actions and is given as

$$\sum_{n\in N^v}\sum_{v=1}^{V} M_{n_p} C_{d_{n_p} v}, \quad \forall p,\ \forall n \tag{36}$$

3.2.7. Assembly costs

This is the cost involved in assembling the modules at the factories to meet the market demand. Assembly cost can vary in different factory locations due to the variation in labor or resource costs. This cost is given as

$$\sum_{u=1}^{U}\left(\sum_{n\in N^u}\sum_{u=1}^{U} M_{n_p u} + \sum_{n\in N^{\phi}}\sum_{z=1}^{z} M_{n_p z}\right) \times C_{pA_u}, \quad \forall p \tag{37}$$

The objective function here is to minimize the transportation costs, inventory costs, disposal costs and assembly costs as mentioned above.

$$\begin{aligned}
\text{Min} & \sum_{w=1}^{W}\sum_{r=1}^{R} Q_{p_r}T_{p_{rw}} + \sum_{j=1}^{J}\sum_{w=1}^{W} Q_{p_w}T_{p_{wj}} + \sum_{n\in N^s}\sum_{j=1}^{J}\sum_{s=1}^{S} D_{n_ps}T_{n_pjs} \\
& + \sum_{n\in N^u}\sum_{j=1}^{J}\sum_{u=1}^{U} M_{n_pu}T_{n_pju} + \sum_{n\in N^x}\sum_{j=1}^{J}\sum_{x=1}^{X} M_{n_p}T_{n_pjx} + \sum_{n\in N^v}\sum_{j=1}^{J} \\
& \times \sum_{v=1}^{V} M_{n_p}T_{n_pjv} + \sum_{h=1}^{H}\sum_{u=1}^{U} D_{h_p}T_{pfg_{uh}} + \sum_{p=1}^{P} Q_pC_p + \sum_{w=1}^{W} Q_{w_p}C_{pi_w} \\
& + \sum_{j=1}^{J} Q_{j_p}C_{pi_j} + \sum_{n\in N^l}\sum_{j=1}^{J} M_{n_pj}C_{in_pj} + \sum_{n\in N^u}\sum_{u=1}^{U} M_{n_pu}C_{in_pu} \\
& + \sum_{w=1}^{W} C_w + \sum_{j=1}^{J} C_j + \sum_{u=1}^{U} C_u + \sum_{n\in N^\phi}\sum_{z=1}^{Z} M_{n_pz}C_{M_{n_pz}} + \sum_{n\in N^s}\sum_{j=1}^{J} \\
& \times \sum_{s=1}^{S} M_{n_ps}C_{R_{n_p}j} + \sum_{n\in N^u}\sum_{j=1}^{J}\sum_{u=1}^{U} M_{n_pu}C_{R_{n_p}j} + \sum_{n\in N^v}\sum_{v=1}^{V} M_{n_p}C_{d_{n_p}v} \\
& + \sum_{u=1}^{U}\left(\sum_{n\in N^u}\sum_{u=1}^{U} M_{n_pu} + \sum_{n\in N^\phi}\sum_{z=1}^{z} M_{n_pz}\right)\times C_{pA_u} \qquad (38)
\end{aligned}$$

Subject to the following constraints.

3.2.8. Capacity constraints

Each warehouse, RPC and factory has a limited capacity given as

$$D_w \geqslant \sum_{p=1}^{P}(V_p \times Q), \quad \forall w \qquad (39)$$

$$D_j \geqslant \sum_{p=1}^{P}\sum_{n=1}^{N}\left(V_{pM_{n_p}} \times \sum_{p=1}^{P}\sum_{n=1}^{N} M_{n_p}\right), \quad \forall j \qquad (40)$$

$$D_{Rej} \geqslant \left(\sum_{n\in N^s}\sum_{s=1}^{S} D_{n_ps} + \sum_{n\in N^u}\sum_{u=1}^{U} M_{n_pu}\right), \quad \forall p,\ \forall j \qquad (41)$$

$$D_x \geqslant \sum_{n\in N^x} M_{n_p}, \quad \forall x \qquad (42)$$

$$D_v \geqslant \sum_{n\in N^v} M_{n_p}, \quad \forall v \qquad (43)$$

All the assigned product and module quantities are defined as non-negative integers.

4. Model implementation

A nine echelon network consisting of five retailers, four warehouses, three RPC's, five spare markets, three factories, one recycling centre, one disposal site, six new module suppliers and six distribution centres has been considered for the model implementation. Consistent to earlier studies (Mabini, Pintelon, & Gelders, 1992; Mitra, 2007; Mostard & Teunter, 2006; Salema, Povoa, & Novais, 2006), a certain percentage (30% in this case) of returned modules of the returned products are assumed to be disposed. Good modules are either sent to the factory for remanufacturing, or to spare market. Also, 10% of the returned modules are assumed to be sent for recycling. If there are mismatch of modules at the remanufacturer, additional new modules are purchased from pre-specified suppliers. The balance of good modules, if any, will be stored in the RPC.

For simple illustration of the model a single returned product with ten modules are considered. Data used for the analysis are given in the Appendix. A returned quantity of 25,000 used products on a monthly basis (cumulative sum of all inputs of used products in Fig. 2) is assumed for the base case. The model is solved using GAMS® software.

The resulting network with allocated and unallocated transportation routes and subsequent allocations of modules and

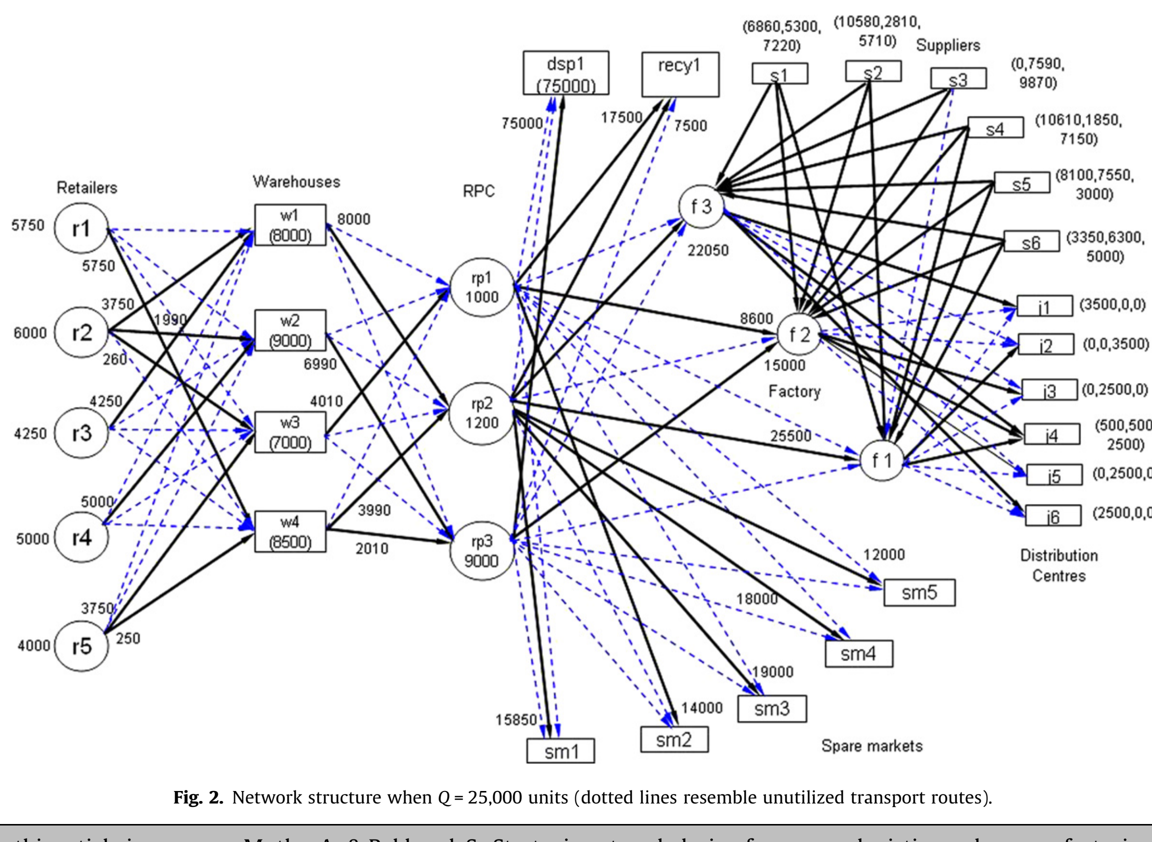

Fig. 2. Network structure when $Q = 25{,}000$ units (dotted lines resemble unutilized transport routes).

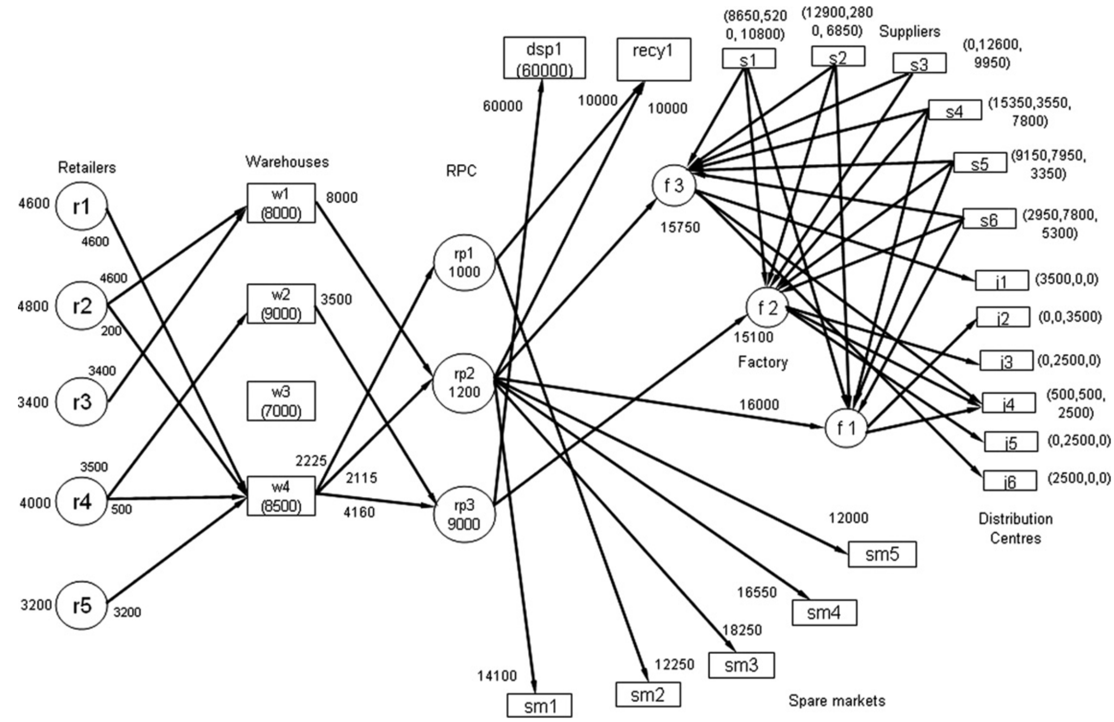

Fig. 3. Network structure when $Q = 20{,}000$ units.

products to different entities are shown in Fig. 2. The result shows that the optimal cost for this network would be around $2,573,750 for acquisition, storing, processing and distributing per month. Further analysis of allocated data shows that the total logistics cost of the system (including transportation, inventory, and fixed and holding costs of warehouse and RPC) is around $415,500 of which transportation cost is about $306,000. Sensitivity analysis showed that even if the transportation cost increases by 50% the optimal solution increases by less than 1%. This analysis shows that in the assumed case, it is not the logistics, but probably the location of collection centre (to get a higher volume of used products) and purchase price of

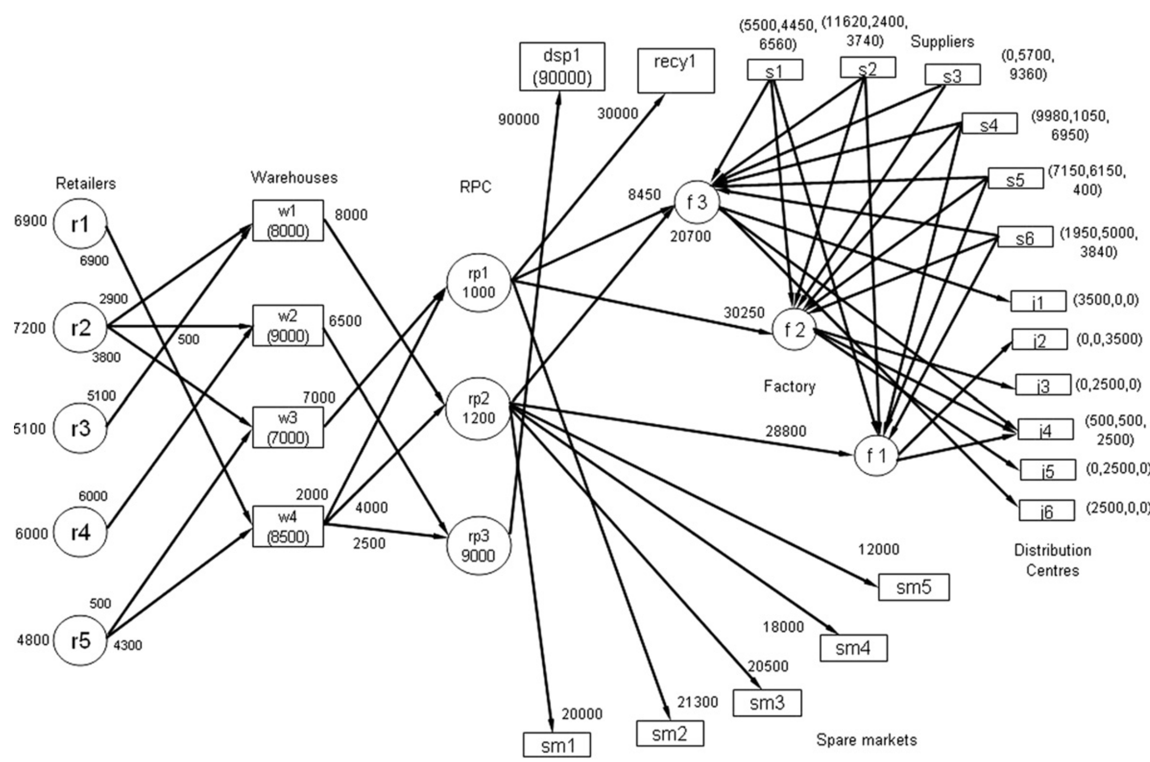

Fig. 4. Network structure when $Q = 30{,}000$ units.

Please cite this article in press as: Mutha, A., & Pokharel, S., Strategic network design for reverse logistics and remanufacturing using new ..., *Computers & Industrial Engineering* (2008), doi:10.1016/j.cie.2008.06.006

Table 3
Processing capacity reduction at RPC

Scenario	RPC 1	RPC 2	RPC 3
0	Base case	Base case	Base case
1	(−)10%	Base case	Base case
2	Base case	(−)10%	Base case
3	Base case	Base case	(−)10%
4	(−)10%	(−)10%	(−)10%

modules (new and old) that has more impact on reverse logistics network decision.

We carried out scenario analysis to understand possible changes in the network with variation in returned quantities with $Q = 20{,}000$ units (Fig. 3) and $Q = 30{,}000$ units (Fig. 4) while keeping all other attributes as constant. This is desired to simulate the effect of changes in the returned quantities on the optimal choice of RL network, if any. The analysis showed that when less number of products ($Q = 20{,}000$ units) are returned (compared to base case $Q = 25{,}000$ units), the system requires only three warehouses (see Fig. 3 where warehouse W_3 has no allocations). However, due to lesser number of modules from the used products, more new modules would be required to fulfill the demand ($N^{\phi} = 133{,}150$ units as compared to $N^{\phi} = 108{,}850$ units for the base case). With this, the cost of procuring new modules increases significantly from around $815,000 in the base case to around $1,002,000.

With a return of 30,000 used products, the number of recovered modules increases (from 71,150 units when $Q = 25{,}000$ to 88,200 units when $Q = 30{,}000$). Therefore, the quantity of new modules procured from the suppliers to meet the market demand reduces to about 91,800. Thus, the cost of procuring new modules also reduces. It is seen from Fig. 4 that remanufacturing factories 'f1' and 'f2' would require fewer new modules due to cost-effective allocations.

Constraints in processing capacities at RPC can also cause changes in the flow of new and used modules. This situation can occur when there are sudden mechanical breakdowns or reallocation of factory resources to meet unanticipated demand for other products produced in the same processing centre. Various scenarios of capacity reductions as shown in Table 3 are tested. Base case in Table 3 refers to the capacities mention in Table A.5 in Appendix. For the first scenario, for example, a 10% reduction in capacity at RPC_1 is assumed while keeping capacities of RPC_2 and RPC_3 to the base case level. All other factors are assumed to be the same as that in the base case.

The analysis provides an insight to some of the key contributors to the overall network cost namely the new module cost (Fig. 5) and the transportation and inventory costs (Fig. 6). With a reduced capacity in a RPC, the cost of purchasing new module increases (Fig. 5). In the base case, the number of recovered modules supplied to the factories by RPC_1, RPC_2 and RPC_3 are 8600; 47,550; and 15,000, respectively. In this case, the demand for new modules (N^{ϕ}) is 108,850 units. In scenario 1, the number of modules recovered and supplied to the factory by RPC_2 reduces to 45,000 (decrease of about 5.36%). However, the demand for new modules (N^{ϕ}) increased by only 2550 (increase of about 2.34%). Also, the supply of modules for recycling decreases from RPC_1 by 2500 modules (decrease of 14.29%) while it increases from RPC_1 to 10,000 modules (increase by 33.3%). In scenario 2, the number of modules recovered and supplied to the factory by RPC_1 is 10,640 (increase of about 23.7%) while the supply from RPC_3 is 10,600 (decrease of about 29.4%). In this scenario, the total number of modules recovered and supplied by all the RPC's is more than the cumulative supply in scenario 1, hence the demand for new modules (N^{ϕ}) decreases by 190 as compared to scenario 1. However, as compared to the base case, the demand for new modules (N^{ϕ}) increases by 2360 (increase of about 2.16%). Also, the RPC_3 supplies 25,000 modules for recycling (total recycling demand). In scenario 3, the quantity of excess modules supplied by RPC_1 is equivalent to the shortage of supply from RPC_3 (9000 modules). The supply of recovered modules from RPC_2 also reduces of about 4.6% causing the demand for new modules (N^{ϕ}) to increase by about 2%. In scenario 4 the supply of recovered modules from RPC_1 increases by 6640 (increase of about 77.2%). However, the supply from RPC_2 and RPC_3 decreases by 4,755 (decrease of about 10%) and 9000 (decrease of about 60%), respectively. Hence the demand for new modules increases significantly to 7115 (increase of about 6.5%). Thus with a change of 10% in the RPC capacity, the new

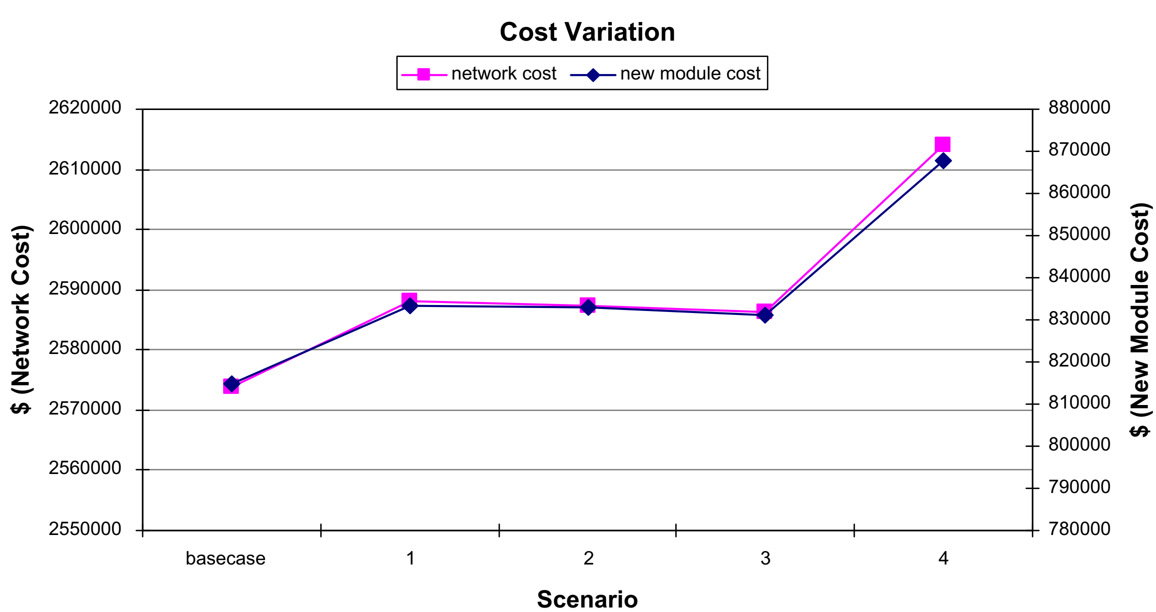

Fig. 5. Network & new module cost variation when $Q = 25{,}000$ units.

Please cite this article in press as: Mutha, A., & Pokharel, S., Strategic network design for reverse logistics and remanufacturing using new ..., *Computers & Industrial Engineering* (2008), doi:10.1016/j.cie.2008.06.006

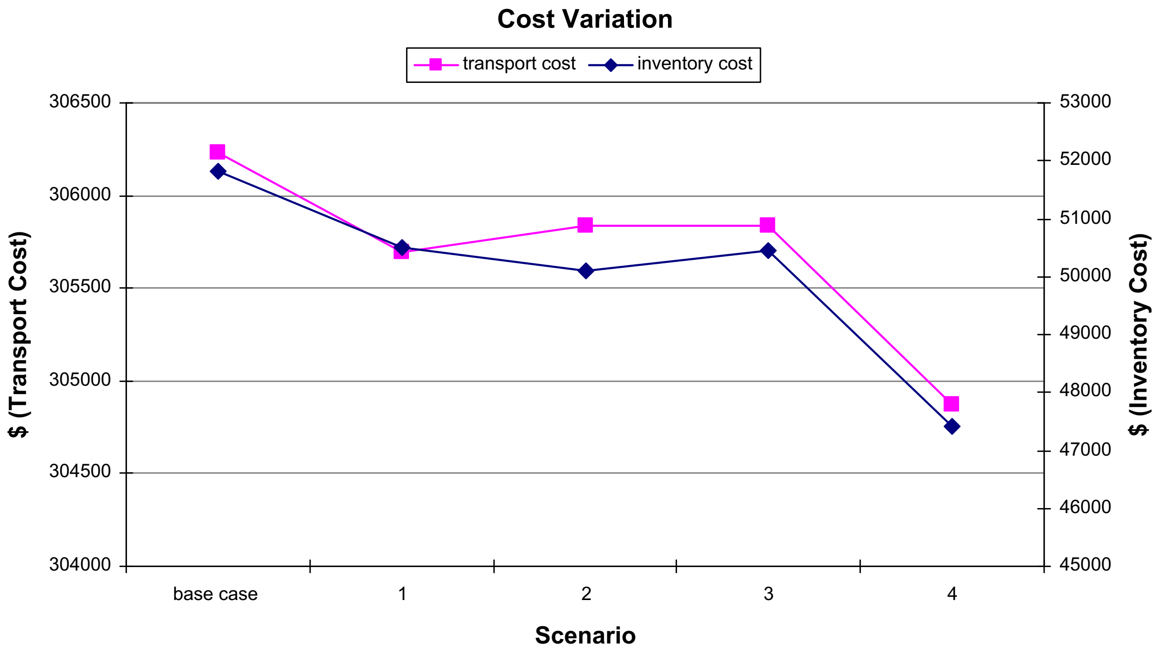

Fig. 6. Transportation and inventory holding cost variation when $Q = 25{,}000$ units.

module cost changes by 2.27% in scenario 1, 2.16% in scenario 2, 1.96% in scenario 3, and about 6.37% in scenario 4. Also, a higher correlation between the network cost and the new module cost for the given scenarios is seen.

Fig. 6 shows the variation in transportation and inventory costs for the scenarios given in Table 3. The figure shows that for the base case in which 71,150 modules are recovered, the inventory cost is about $51,800. For scenario 1, since only 68,600 usable modules are recovered, the inventory carrying cost decreases to about $50,500. Similarly, the transport cost also reduces to about $305,700 (as compared to the base case in which the transport cost was about $306,200). In scenario 2, as seen from Fig. 5, the number of recovered used modules increases to 68,790 (since the number of new modules to be purchased decreases). Hence, the transport cost increases in scenario 2. However the inventory cost further reduces to about $50,100. This is because, RPC_3, which has a high average per module inventory cost, recovers 4400 fewer modules than the base case. In scenario 3, a total of 68,945 usable modules are recovered from the returned products, hence the inventory carrying cost increases to about $50,450. In scenario 4, the total number of recovered modules reduces drastically to 64,035. Hence, the inventory and transport costs reduce significantly to $47,400 and $304,900, respectively. When the processing capacities at the RPC's are constrained, the total quantity of recovered modules transported from the RPC's to the factories and spare markets reduces (as seen in Fig. 5, the quantity of new modules procured increases). This results in a decrease in the transport costs. Hence, as there are fewer remanufactured modules at the factory, the inventory costs at the factories also reduce.

Various legislations are forcing companies to manufacture products that have higher levels of recyclable materials and products (WEEE Directive 2002/95/EC and 2002/96/EC; Yang, 1995). Hence, a higher percentage of recyclable modules and lower percentage of disposable modules are assumed for sensitivity analysis. The scenarios for recyclable and disposal percentage variations are given in Table 4. Assuming all other costs as constant, it is found that the total network cost decreases with an increase in the percentage of recyclable content of the product. This is because of reduction in disposal costs. Thus, companies may develop products with modules and materials that are highly recyclable.

Table 4
Variation in disposal and recycling percentage

Scenario	Disposal %	Recycling %	Network cost
0 (base case)	30	10	2573756
1	20	20	2406854
2	10	30	2240171

By using a nine echelon network, it is shown that the proposed model can be used for strategic decision making to design a RL network. Scenario analysis is given to reflect the situation on changes in capacities at the processing centres and receipt of fewer or more returned products from the customer. By assuming inventory holding costs at the factories for unused products, real life situation when the demand are not met as expected or when factories are not able to process all the modules into products due to various constraints are reflected. Also, if the number of usable modules recovered in the RPC's is in excess of the demand for remanufacturing and spare markets, they are stored in the RPC's (incurring inventory carrying cost) till further demand is received. This economic decision making helps in further optimizing the network cost. Most of all, this research demonstrates that the model is useful to study network design for a RL situation.

5. Conclusions

This paper proposes a model to for designing reverse logistics networks. An idea presented in this paper is allowing only a portion of capacity in warehouses, RPC's and factories for RL. This can also simulate current pattern used by some of the industry to use existing warehouses, dismantling centres and factory lines for returned products. Due to the difficulty in establishing whole new entities to cater to the needs for RL, some companies segregate

Please cite this article in press as: Mutha, A., & Pokharel, S., Strategic network design for reverse logistics and remanufacturing using new ..., *Computers & Industrial Engineering* (2008), doi:10.1016/j.cie.2008.06.006

their capacities to handle new products and returned products. This way, companies would have flexibility to produce new or remanufactured products as per the demand.

We believe that when the demand for remanufactured products increase there would be a need to mix and match old and new modules. Therefore, the model incorporates an echelon for suppliers that can provide various quantities of new module on need basis. The model also considers the demand of modules in the spare market as it would generally fetch higher value (compared to the final product) per module for the companies. With advancement in technology and design processes, it is possible to estimate the number and type of modules that might have to be disposed. Therefore, we have assumed certain percentages of modules going to recycling and disposal centres.

The model brings out an important conclusion in the forefront. That is transportation and other logistics costs may not be an important factor in the design of a network. Rather, the cost of reprocessing, remanufacturing, and the cost of new modules can be the driving factor for the choice of a reverse logistics network. Throughout simulation with different quantities of returned product, the cost of new module is seen as an important factor in network cost. Therefore, it might be beneficial for the decision makers to locate reprocessing centre at a location where resources (like labour, energy, and land) are cheaper and to locate remanufacturing centres at places where new modules of the remanufactured products can be obtained at a cheaper rate.

We believe that the generic model proposed here serves as a valuable tool for strategic decision making in RL. We have assumed a differential cost for the same modules supplied by different suppliers. However, an important extension could be to model module costs with respect to required quantities. Obviously, suppliers would not be able to offer a discount on modules when demand quantities are lower. Also, waiting time for a returned product at different facilities can be a random variable. This requires an extension of the model by considering variable inventory cost at different facilities. Another extension in the model could be to combine processing centres with warehouse locations. Combining of processing activities with warehousing could generate extra revenues for the warehouses. As reported in Pokharel (2005), such value adding activities can make warehouses more cost effective.

Appendix A

The used product is assumed to have ten unique modules. The transport costs are given in Table A.1 and the inventory carrying cost (ICC) are given in Table A.2. The costs associated with reprocessing, assembling and disposal activities are given in Table A.3. Fixed costs of the facilities and the product acquisition costs are given in Table A.4. The data on the total quantity of products supplied by the retailers (Q) and the storage capacity of the warehouse and RPC, the production capacity of each factory and demand are given in Table A.5. The capacity constraint of the suppliers and the cost of new modules from each supplier to each factory are given in Table A.6.

Table A.1
Data on transportation costs

Retailer to warehouse – $R_r(W_w)$ ($/product)	Warehouse to RPC – $W_w(J_j)$ ($/product)	RPC to factory $J_j(U_u)$ ($/module)	RPC to spare market $J_j(S_s)$ ($/module)	RPC to disposal $J_j(V_v)$ ($/module)	RPC to recycing $J_j(X_x)$ ($/module)	Factory to DC $U_u(H_h)$ ($/product)
(0.3, 0.54, 0.33, 0.38, 0.26, 0.42, 0.29, 0.36, 0.3, 0.5, 0.39, 0.42, 0.33, 0.3, 0.36, 0.33, 0.42, 0.44, 0.3, 0.35)	(0.95, 0.83, 0.90, 1.11, 1.05, 1.02, 1.16, 1.19, 1.23, 0.87, 0.77, 0.83)	(0.24, 0.23, 0.24, 0.21, 0.24, 0.23, 0.24, 0.22, 0.23)	(0.9, 0.75, 0.89, 0.78, 0.81, 0.86, 0.84, 0.86, 0.75, 0.78, 0.89, 0.8, 0.87, 0.78, 0.78)	(2.25, 2.75, 2.20)	(4.65, 2.80, 3.35)	U_1(1.59, 3.18, 2.85, 0.78, 1.71, 2.43, 2.52, 2.40, 2.28, 0.75, 1.47, 2.73, 2.10, 2.07, 2.58, 0.78, 1.89, 2.79)

Table A.2
Data on inventory carrying cost (ICC)

ICC at warehouse W ($/prod/month)	ICC at RPC J ($/prod/month)	ICC at factory U ($/prod/month)	ICC at RPC J ($/module/month)
(716.75, 645.00, 403.25, 537.50)	(1875, 2100, 1600)	U_1(0.28, 0.52, 0.83, 0.42, 0.48, 0.57, 1.0, 0.47, 0.45, 0.30) U_2(0.35, 0.58, 1.03, 0.65, 0.53, 0.90, 1.3, 0.75, 0.63, 0.57) U_3(0.32, 0.55, 0.92, 0.50, 0.50, 0.73, 1.13, 0.62, 0.55, 0.43)	J_1(2.18, 1.16, 0.80, 0.22, 0.68, 1.16, 0.60, 0.76, 0.46, 1.20) J_2(1.56, 1.38, 0.84, 0.26, 0.94, 1.30, 0.70, 0.70, 0.50, 1.16) J_3(1.20, 1.36, 0.72, 0.30, 1.10, 1.34, 0.66, 0.82, 0.56, 1.12)

Table A.3
Data on reprocessing, disposal and assembly costs

Reprocessing cost at RPC J ($($J_j$)/modules)	Disposal cost at site V ($($V_v$)/module)	Assembly cost at factory U ($($U_u$)/module)
J_1(0.64, 0.58, 0.16, 0.36, 0.30, 0.48, 0.50, 0.58, 1.04, 1.00) J_2(0.68, 0.64, 0.24, 0.29, 0.29, 0.48, 0.60, 0.52, 0.88, 0.76) J_3(0.66, 0.62, 0.2, 0.31, 0.28, 0.45, 0.55, 0.55, 0.92, 0.84)	(0.99, 1.08, 1.64, 0.86, 2.27, 3.58, 2.25, 1.03, 2.09, 1.78)	U_1 (0.28, 0.73, 0.05, 0.25, 0.18, 0.56, 0.46, 0.52, 0.12, 0.25) U_2(0.35, 0.71, 0.08, 0.22, 0.16, 0.60, 0.50, 0.56, 0.09, 0.29) U_3 (0.32, 0.72, 0.06, 0.23, 0.17, 0.58, 0.48, 0.54, 0.11, 0.27)

Table A.4
Data on fixed cost

Fixed cost of warehouse ($/month)	Fixed cost of RPC ($/month)	Fixed cost of factory ($/month)	Product acquisition cost ($/product)
(5750, 5500, 4900, 6900)	(9350, 6700, 5500)	(4850, 4550, 4600)	21.5

Table A.5
Data on supply, storage capacity, demand at DC and capacity constraint at factory

Supply (Q) from retailer R (units)	Storage capacity at warehouse W (prod)	Storage capacity at RPC J (prod)	Demand for modules in Spare market $S_s(m_i \dots m_n)$ (units)	Demand at DC h = 1–6 (prod)	Capacity constraint at factory U (prod)
(5750, 6000, 4250, 5000, 4000)	(8000, 9000, 7000, 8500)	(10000, 12000, 9000)	S_1(2400, 600, 1000, 3500, 1200, 4250, 100, 0, 500, 2300) S_2(0, 3500, 2500, 0, 3500, 1900, 0, 2000, 600, 0) S_3(2500, 2500, 2400, 1500, 2000, 800, 1500, 2500, 900, 2400) S_4(2000, 550, 1800, 2700, 800, 1000, 1800, 1500, 4000, 1850) S_5(0, 1850, 1500, 0, 800, 800, 4100, 500, 1500, 950)	(3500, 3500, 2500, 3500, 2500, 2500)	(6500, 5500, 6000)

Table A.6
Data on monthly supply constraint and cost of new modules

Monthly supply constraint $Z_z(m_i \dots m_n)$ (modules)	Cost of new module $Z_z(m_i \dots m_n) - U_u$ (\$/module) (including transportation costs)
Z_1(1900, 2750, 2580, 1800, 1300, 1800, 1800, 2000, 1750, 2260)	Z_1(3, 6.25, 11.25, 5.3, 6.6, 6.85, 13.3, 7.45, 5.75, 8.25) – U_1 Z_1(3.3, 6.5, 11.5, 5.6, 6.8, 7.05, 13.5, 7.65, 6, 8.75) – U_2 Z_1(3.2, 6.4, 11.35, 5.75, 6.25, 6.5, 13.35, 7.5, 5.6, 8.25) – U_3
Z_2(1700, 2000, 2250, 1850, 2500, 2200, 2100, 1750, 1850, 1800)	Z_2(2.9, 6.5, 11.2, 5.25, 6.45, 6.9, 13.3, 7.35, 5.8, 8.2) – U_1 Z_2(3.25, 6.6, 11.6, 5.65, 6.75, 7.15, 13.55, 7.8, 6.25, 8.5) – U_2 Z_2(3.15, 6.5, 11.3, 5.65, 6.5, 6.65, 13.3, 7.15, 5.8, 8.4) – U_3
Z_3(2700, 2500, 1750, 1750, 1700, 2000, 2500, 1850, 1800, 1600)	Z_3(3.15, 6.6, 11.35, 5.3, 6.5, 6.95, 13.4, 7.5, 5.8, 8.5) – U_1 Z_3(3.15, 6.6, 11.55, 5.5, 6.6, 6.95, 13.4, 7.7, 6.15, 8.75) – U_2 Z_3(3.15, 6.35, 11.35, 5.5, 6.35, 6.7, 13.45, 7.25, 5.65, 8.6) – U_3
Z_4(2360, 2400, 2000, 2000, 1800, 2300, 2000, 1450, 2000, 1800)	Z_4(2.9, 6.35, 11.15, 5.2, 6.55, 6.95, 13.35, 7.4, 5.75, 8.2) – U_1 Z_4(3.2, 6.55, 11.45, 5.6, 6.65, 7, 13.35, 7.75, 6.1, 8.65) – U_2 Z_4(3.2, 6.35, 11.4, 5.6, 6.3, 6.55, 13.35, 7.35, 5.75, 8.5) – U_3
Z_5(1800, 2100, 2500, 1950, 2100, 2400, 1600, 1500, 2250, 2100)	Z_5(3.05, 6.25, 11.15, 5.2, 6.5, 6.85, 13.45, 7.35, 5.9, 8.45) – U_1 Z_5(3.15, 6.5, 11.45, 5.75, 6.7, 6.95, 13.45, 7.65, 6.05, 8.6) – U_2 Z_5(3.25, 6.45, 11.45, 5.7, 6.4, 6.85, 13.45, 7.2, 5.7, 8.45) – U_3
Z_6(1540, 2000, 2000, 2250, 2600, 1700, 2000, 1800, 1800, 2400)	Z_6(3.1, 6.45, 11.3, 5.25, 6.45, 7.05, 13.5, 7.4, 5.75, 8.35) – U_1 Z_6(3.25, 6.65, 11.4, 5.5, 6.6, 7.05, 13.5, 7.8, 6, 8.7) – U_2 Z_6(3.3, 6.45, 11.3, 5.55, 6.35, 6.6, 13.5, 7.4, 5.75, 8.35) – U_3

References

Alshamrani, A., Mathur, K., & Ballou, Ronald H. (2007). Reverse logistics: Simultaneous design of delivery routes and return strategies. *Computers and Operations Research, 34*, 595–619.

Barros, A. I., Dekker, R., & Scholten, V. (1998). A two-level network for recycling sand: A case study. *European Journal of Operational Research, 110*, 199–214.

Beamon, B. A., & Fernandes, C. (2004). Supply-chain network configuration for product recovery. *Production Planning and Control, 15*(3), 270–281.

Berger, T., & Debaillie, B. (1997). *Location of disassembly centres for re-use to extend an existing distribution network*. Belgium: University of Leuven.

Beullens, P. (2004). Reverse logistics in effective recovery of products from waste materials. *Reviews in Environmental Science and Bio/Technology, 3*(4), 283–306.

Biehl, M., Prater, M., & Realff, M. J. (2007). Assessing performance and uncertainty in developing carpet reverse logistics systems. *Computers and Operations Research, 34*, 443–463.

Bloemhof-Ruwaard, J., Fleischmann, M., & van Nunen, J. (1999). Reviewing distribution issues in reverse logistics. In M. G. Speranza & P. Stahly (Eds.), *New trends in distribution logistics*. Springer-Verlag.

Bowersox, D., & Closs, D. (1996). *Logistical management: The integrated supply chain process*. London: McGraw-Hill International Editions.

Carter, C., & Ellram, L. (1998). Reverse logistics: A review of literature and framework for future investigation. *Journal of Business Logistics, 19*(1), 85–102.

Daugherty, P., Autry, C., & Ellinger, A. (2001). Reverse logistics: The relationship between resource commitment and program performance. *Journal of Business Logistics, 22*(1), 107–123.

De Koster, R. B. M., de Brito, M. P., & van de Vendel, M. A. (2002). Return handling: An exploratory study with nine retailer warehouses. *International Journal of Retail and Distribution Management, 30*(8), 407–421.

Dethloff, J. (2001). Vehicle routing and reverse logistics: The vehicle routing problem with simultaneous delivery and pick-up. *OR Spectrum, 23*, 79–96.

Dowlatshahi, S. (2000). Developing a theory of reverse logistics. *Interfaces, 30*(3), 143–155.

Dowlatshahi, S. (2005). A strategic framework for the design and implementation of remanufacturing operations in reverse logistics. *International Journal of Production Research, 43*(16), 3455–3480.

Du, F., & Evans, G. (2008). A bi-objective reverse logistics network analysis for post-sale service. *Computers and Operations Research, 35*, 2617–2634.

Fernandez, I., & Kekale, T. (2005). The influence of modularity and clock speed on reverse logistics strategy: Implications for the purchasing function. *Journal of Purchasing and Supply Management, 11*, 193–205.

Ferrer, G., & Whybark, C. D. (2000). From garbage to goods: Successful remanufacturing systems and skills. *Business Horizons, 43*(6), 55–64.

Fleischmann, M. (2001). *Quantitative models for reverse logistics*. Springer. p. 41.

Fleischmann, M., Beullens, P., Bloemhof-Ruwaard, J. M., & van Wassenhove, L. N. (2001). The impact of product recovery on logistics network design. *Production and Operations Management, 10*(2), 156–173.

Fleischmann, M., Bloemhof-Ruwaard, J. M., Dekker, R., van der Laan, E. A., van Nunen, J. A. E. E., & van Wassenhove, L. N. (1997). Quantitative models for reverse logistics: A review. *European Journal of Operational Research, 103*, 1–17.

Franke, C., Basdere, B., Ciupek, M., & Seliger, S. (2006). Remanufacturing of mobile phones-capacity, program and facility adaptation planning. *Omega, 34*, 562–574.

Fredrikson, P. (2006). Mechanisms and rationales for the coordination of a modular assembly system – the case of Volvo cars. *International Journal of Operation and Production Management, 26*(4), 250–370.

Guide, VDR., Jayaraman, V., & Srivastava, R. (1999). The effect of lead time variation on the performance of disassembly release mechanism. *Computers and Industrial Engineering, 36*, 759–779.

Gungor, A., & Gupta, S. (1998). Disassembly sequence planning for products with defective parts in product recovery. *Computers and Industrial Engineering, 35*(1–2), 161–164.

Gungor, A., & Gupta, S. (1999). Issues in environmentally conscious manufacturing and product recovery: A survey. *Computers and Industrial Engineering, 36*, 811–853.

Gupta, S., & Isaacs, J. (1997). Value analysis of disposal strategies for automobiles. *Computers and Industrial Engineering, 33*(1–2), 325–328.

Heese, H. S., Cattani, K., Ferrer, G., Gilland, W., & Roth, A. V. (2005). Competitive advantage through take-back of used products. *European Journal of Operational Research, 164*, 143–157.

Hwang, H., Oh, Y., & Gen, M. (2005). An inventory policy for recycling system. In V. Kachitvichyanukul, U. Purintrapiban, & P. Utayopas (Eds.), *Proceedings of the 2005 international conference on simulation and modeling, Thailand*.

Jahre, M. (1995). Household waste collection as a reverse channel – a theoretical perspective. *International Journal of Physical Distribution and Logistics Management, 25*(2), 39–55.

Jayaraman, V., Guide, V. D. R., Jr., & Srivastava, R. (1999). A closed-loop logistics model for remanufacturing. *Journal of the Operational Research Society, 50*, 497–508.

Jayaraman, V., Patterson, R., & Rolland, E. (2003). The design of reverse distribution networks: Models and solution procedures. *European Journal of Operational Research, 150*, 128–149.

Kara, S., Rugrungruang, F., & Kaebernick, H. (2007). Simulation modeling of reverse logistics networks. *International Journal of Production Economics, 106*, 61–69.

Kim, K., Song, I., Kim, J., & Jeong, B. (2006). Supply planning model for remanufacturing system in reverse logistics environment. *Computers and Industrial Engineering, 51*, 279–287.

Koh, S.-G., Hwang, H., Sohn, K.-I., & Ko, C.-S. (2002). An optimal ordering and recovery policy for reusable items. *Computers and Industrial Engineering, 43*, 59–73.

Krikke, H., Pappis, C., Tsoulfas, G., & Bloemhof-Ruwaard, J. (2001). Design principles for closed loop supply chains: Optimizing economic, logistic and environmental performance. ERIM Report Series Research in Management, ERS-2001-62-LIS.

Krikke, H. R., van Harten, A., & Schuur, P. C. (1999a). Business case Oce: Reverse logistic network re-design for copiers. *OR Spectrum, 21*, 381–409.

Krikke, H. R., van Harten, A., & Schuur, P. C. (1999b). Business case Roteb: Recovery strategy for monitors. *Computers and Industrial Engineering, 36*, 739–757.

Kroon, L., & Vrijens, G. (1995). Returnable containers: An example of reverse logistics. *International Journal of Physical Distribution and Logistics Management, 25*(2), 56–68.

Krumwiede, D., & Sheu, C. (2002). A model for reverse logistics entry by third-party providers. *Omega, 30*, 325–333.

Kusumastuti, R., Piplani, R., & Lim, G. (2004). An approach to design reverse logistics networks for product recovery. In *Proceedings of IEEE international engineering management conference, Singapore* (pp. 1239–1243).

Lambert, A. (2002). Determining optimum disassembly sequences in electronic equipment. *Computers and Industrial Engineering, 43*, 553–575.

Lee, D.-H., & Dong, M. (2007). A heuristic approach to logistics network design for end-of-lease computer products recovery. *Transportation Research E*. doi:10.1016/j.tre.2006.11.003.

Louwers, D., Kip, B. J., Peters, E., Souren, F., & Flapper, S. D. P. (1999). A facility location allocation model for reusing carpet materials. *Computers and Industrial Engineering, 36*, 855–869.

Lu, Z., & Bostel, N. (2007). A facility location model for logistics systems including reverse flows: The case of remanufacturing activities. *Computers and Operations Research, 34*, 299–323.

Mabini, M., Pintelon, L., & Gelders, L. (1992). EOQ type formulations for controlling repairable inventories. *International Journal of Production Economics, 28*, 21–33.

Min, H., Ko, H.-J., & Ko, C.-S. (2006a). A genetic algorithm approach to developing the multi-echelon reverse logistics network for product returns. *Omega, 34*, 5–69.

Min, H., Ko, H.-J., & Ko, C.-S. (2006b). The spatial and temporal consolidation of returned products in a closed-loop supply chain network. *Computers and Industrial Engineering, 51*, 309–320.

Mitra, S. (2007). Revenue management for remanufactured products. *Omega, 35*, 553–562.

Mok, H., Kim, H., & Moon, K. (1998). Disassemblability of mechanical parts in automobile for recycling. *Computers and Industrial Engineering, 33*(3–4), 621–624.

Mostard, J., & Teunter, R. (2006). The newsboy problem with resalable returns: A single period model and case study. *European Journal of Operational Research, 169*, 81–96.

Murphy, P. (1986). A preliminary study of transportation and warehousing aspects of reverse distribution. *Transportation Journal, 34*(1), 48–56.

Nagel, C., & Meyer, P. (1999). Caught between ecology and economy: End-of-life aspects of environmentally conscious manufacturing. *Computers and Industrial Engineering, 36*, 781–792.

Pati, R., Vrat, P., & Kumar, P. (2006). A goal programming model for paper recycling system. *Omega*. doi:10.1016/j.omega.2006.04.014.

Pochampally, K., & Gupta, S. (2005). Strategic planning of a reverse supply chain network. *International Journal of Integrated Supply Management, 1*(4), 421–441.

Pochampally, K., Gupta, S., & Kamarthi, S. (2004). Identification of potential recovery facilities for designing a reverse supply chain network using physical programming. In S. Gupta (Ed.), *Proceeding of SPIE, environmentally conscious manufacturing 3* (Vol. 5262, pp. 139–146).

Pohlen, T., & Farris, M. (1992). Reverse logistics in plastics recycling. *International Journal of Physical Distribution and Logistics Management, 22*(7), 35–47.

Pokharel, S. (2005). Perception on information and communication technology perspectives in logistics: A study of transportation and warehouses sectors in Singapore. *Journal of Enterprise Information Management, 18*(2), 136–149.

Prahinski, C., & Kocabasoglu, C. (2006). Empirical research opportunities in reverse supply chains. *Omega, 34*, 519–532.

Raimer, G. (1997). In reverse. *Materials Management and Distribution, 12*(3), 12–13.

Ravi, V., Ravi, S., & Tiwari, M. (2005). Analyzing alternatives in reverse logistics for end-of-life computers: ANP and balanced scorecard approach. *Computers and Industrial Engineering, 48*, 327–356.

Realff, M. J., Ammons, J. C., & Newton, D. (2000). Strategic design of reverse production systems. *Computers and Chemical Engineering, 24*, 991–996.

Realff, M. J., Ammons, J. C., & Newton, D. (2004). Robust reverse production system design for carpet recycling. *IIE Transactions, 36*(8), 767–776.

Reimer, B., Sodhi, M., & Jayaraman, V. (2006). Truck sizing models for recyclables pick-up. *Computers and Industrial Engineering, 51*, 621–636.

Rogers, D. (2001). RLEC project plans, p-18, Livonia, MI, October.

Rogers, D., & Tibben-Lembke, R. (1999). *Going backwards: Reverse logistics trends and practices*. Pittsburg, PA: Reverse Logistics Executive Council Press.

Salema, M., Povoa, A., & Novais, A. (2006). A warehouse-based design model for reverse logistics. *Journal of the Operational Research Society, 57*, 615–629.

Salema, M., Povoa, A., & Novais, A. (2007). An optimization model for the design of a capacitated multi-product reverse logistics network, with uncertainty. *European Journal of Operational Research, 179*, 1063–1077.

Savaskan, R. C., Bhattacharya, S., & van Wassenhove, L. N. (2004). Closed-loop supply chain models with product remanufacturing. *Management Science, 50*(2), 239–252.

Schultmann, F., Zumkeller, M., & Rentz, O. (2006). Modeling reverse logistic tasks within closed-loop supply chains: An example from the automotive industry. *European Journal of Operational Research, 171*, 1033–1050.

Shih, L. (2001). Reverse logistics system planning for recycling electrical appliances and computers in Taiwan. *Resources, Conservation and Recycling, 32*, 55–72.

Spengler, T., Puchert, H., Penkuhn, T., & Rentz, O. (1997). Environmental integrated production and recycling management. *European Journal of Operational Research, 97*, 308–326.

Stock, J. R. (1992). Reverse logistics. White Paper, Council of Logistics Management, Oak Brook.

Teunter, R., Van der Laan, E., & Inderfurth, K. (2000). How to set the holding cost rates in average cost inventory models with reverse logistics. *Omega, 28*, 409–415.

Tibben-Lembke, R. S. (2002). Life after death: Reverse logistics and the product life cycle. *International Journal of Physical Distribution and Logistics Management, 32*(3), 223–244.

Tibben-Lembke, R., & Rogers, D. S. (2002). Differences between forward and reverse logistics. *Supply Chain Management: An International Journal, 7*(5), 271–282.

Ulrich, K., & Tung, K. (1991). Fundamentals of product modularity. In *Proceedings of the 1991 ASME design engineering technical conferences – conference on design/manufacture integration, Miami, FL*.

Walther, G., & Spengler, T. (2005). Impact of WEEE-directive on reverse logistics in Germany. *International Journal of Physical Distribution and Logistics Management, 35*(5), 337–361.

WEEE Directive – Directive 2002/96/EC – Official Journal of the European Union (2007). <http://eur-lex.europa.eu/LexUriServ/site/en/oj/2003/l_037/l_03720030213en00240038.pdf> and <http://europa.eu.int/comm/environment/waste/weee_index.htm> Accessed 26.11.07.

Wojanowski, R., Verter, V., & Boyaci, T. (2007). Retail-collection network design under deposit-refund. *Computers and Operations Research, 34*, 324–345.

Yang, G. (1995). Urban waste recycling in Taiwan. *Resources, Conservation and Recycling, 13*, 15–26.

Zhou, L., Naim, M., & Wang, Y. (2007). Soft systems analysis of reverse logistics battery recycling in China. *International Journal of Logistics: Research and Applications, 10*(1), 57–70.