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Network design for reverse logistics☆

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Abstract

Collection and recycling of product returns is gaining interest in business and research worldwide. Growing green concerns and advancement of green supply chain management (GrSCM) concepts and practices make it all the more relevant. Inputs from literature and informal interviews with 84 stakeholders are used to develop a conceptual model for simultaneous location–allocation of facilities for a cost effective and efficient reverse logistics (RL) network. We cover costs and operations across a wide domain and our proposed RL network consists of collection centers and two types of rework facilities set up by original equipment manufacturers (OEMs) or their consortia for a few categories of product returns under various strategic, operational and customer service constraints in the Indian context.

In this paper, we provide an integrated holistic conceptual framework that combines descriptive modeling with optimization techniques at the methodological level. We also provide detailed solutions for network configuration and design at the topological level, by carrying out experimentation with our conceptual model. Our findings provide useful insights to various stakeholders and suggest avenues for further research.

Keywords: Reverse logistics; Product returns; Location–allocation of facilities; Value recovery; Green supply chain management; India

1. Introduction

Green supply chain management (GrSCM) is gaining increasing interest among researchers and practitioners of operations and supply chain management. Three drivers (economic, regulatory and consumer pressure) drive GrSCM worldwide. It integrates sound environmental management choices with the decision-making process for the conversion of resources into usable products. GrSCM has its roots in 'environmental management orientation of supply chains'. Producing environmentally friendly products has become an important marketing element that has stimulated a number of companies to explore options for product take-back and value recovery [1].

Managers have been giving increasing importance to the environmental issues, their impact on operations and potential synergies [2,3] since the early 1990s. Earlier literature is generally restricted to the plant or firm level focusing on green purchasing, industrial ecology, industrial ecosystems and corporate environment strategies [3]. Gradually, environmental management aroused increased interest in the field of supply chain management resulting in a growing literature on green supply chains [4–6].

For the purpose of this paper, we consider GrSCM as defined by Srivastava [4]. He defines GrSCM as

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"Integrating environmental thinking into supply chain management including product design, material sourcing and selection, manufacturing processes, delivery of the final product to the consumers as well as end-of-life management of the product after its useful life". An interesting and significant trend in GrSCM has been the recognition of the strategic importance of reverse logistics (RL) as evident from classification and categorization of the existing GrSCM literature by Srivastava [4] shown in Fig. 1.

RL shall become vital as service management activities and take-back for products such as automobiles, refrigerators and other white goods, cellular handsets, lead-acid batteries, televisions, personal computers (PCs), etc. increase in future. A well-managed RL network cannot only provide important cost savings in procurement, recovery, disposal, inventory holding and transportation but also help in customer retention. Since RL operations and the supply chains they support are significantly more complex than traditional manufacturing supply chains, an organization that succeeds in meeting the challenges presents a formidable advantage not easily replicable by its competitors [7].

Today, India is the fourth largest country in terms of purchasing power parity (PPP) and constitutes one of the fastest growing markets in the world [5]. However, RL is yet to receive the desired attention and is generally carried out by the unorganized sector for some recyclable materials such as paper and aluminum. Some companies in consumer durables and automobile sectors have introduced exchange offers to tap customers who already own such products. The returned products are sold either *as it is* or after refurbishment by third parties.

Successful exchange offers have been marketing focused and no original equipment manufacturer (OEM) has come up with repair and refurbishing or remanufacturing facilities for the returned products and their sale. A summary of product–market characteristics for the wide category of products covered in our study is presented in Table 1. The cumulative annual growth rate (CAGR) shown is for the sales in the past decade and the expected demand in the next decade.

We cover the literature on GrSCM, primarily focusing on 'RL'. We do not consider literature and practices related to green logistics as the issues are more of operational rather than strategic nature and may not be significant in the RL network design per se. We also do not focus in detail on literature on corporate environmental behavior, green purchasing, industrial ecology and industrial ecosystems as it is generally either regulatory-driven or firm-specific. We rather focus more on RL from resource-based viewpoint as establishment of efficient and effective RL and value recovery networks is a pre-requisite for efficient and profitable recycling and remanufacturing. This has received less attention in the GrSCM literature so far.

This paper is further organized as follows. In Section 2, we describe briefly our methodology in light of our objective. This is followed by contextual literature review in Section 3. To address some of the research issues and gaps related to designing RL networks for product returns, we develop a conceptual model in Section 4. The development of the corresponding mathematical model formulation for optimizing the decision-making is described in Section 5. Data collection in the Indian context is described in Section 6. Experimentation results for a few scenarios for decision-making using our model are discussed in Section 7. In Section 8, we conclude by describing the contributions as well as the limitations of our work and also suggest directions for further research.

2. Methodology

Our methodology consists of a theoretical part (literature review and conceptual model development) and an applied part (maximizing profits for various scenarios in practical settings using a hierarchical optimization model and drawing useful managerial insights and implications). A focused literature review seems to be a valid approach, as it is a necessary step in structuring a research field and forms an integral part of any research conducted. We focus mainly on RL literature deriving from related areas like natural resource based view of the firm, GrSCM, supply chain risk, etc. to maintain the theoretical roots and linkages. We identify a few issues and gaps as well as challenges and opportunities. Our endeavor is to highlight the importance of RL and develop a more formal framework for analyzing the RL and value recovery network design. To achieve this, we develop a bi-level optimization model; use secondary data for product returns for a period of 10 years; conduct informal interviews with 84 stakeholders to gauge and estimate various costs and other parameters; and finally derive important strategic and operational implications for various stakeholders.

3. Literature review

The resource-based-view of the firm draws primarily from Hart [8] who proposes a theory of competitive advantage based upon the firm's relationship to the natural environment. He provides a conceptual framework

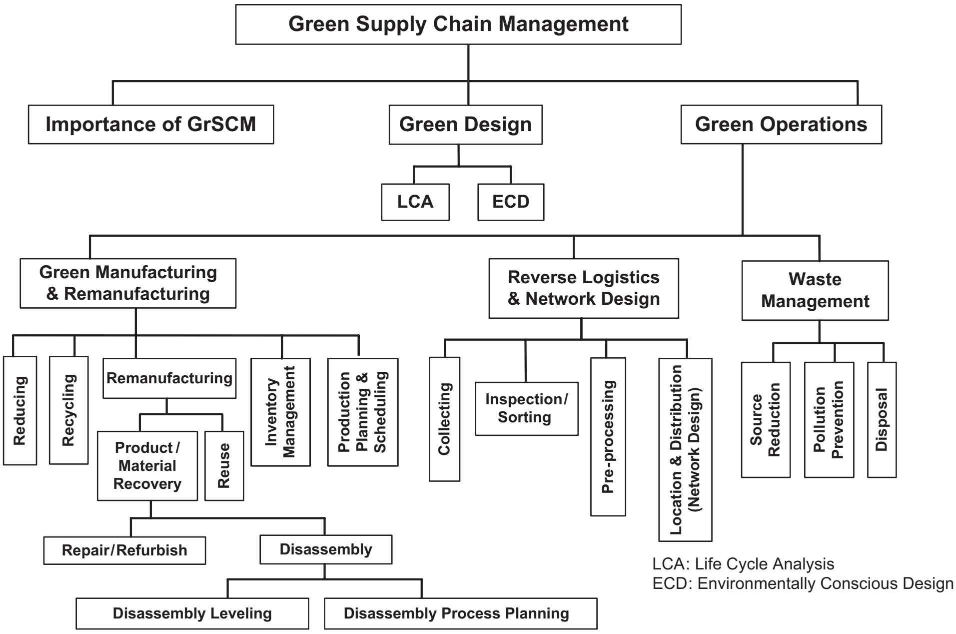

Fig. 1. Classification and categorization of existing GrSCM literature. *Source*: Srivastava [4].

Table 1
Product–Market characteristics of products covered in the study

Product category	Product variety	Product ownership	Sales CAGR (%)	Demand CAGR (%)	Market characteristics
Television sets	Large	High	6.5	4.5	Large and still growing. Highly segmented. Features being added. Stiff competition. Many players.
Passenger cars	Medium	Low	11.7	11.8	Medium and growing. Clear segmentation. Enhancements. Established and new players.
Refrigerators	Large	Medium	7.8	9.7	Large and growing. Segmented. New features. Stiff competition.
Washing machines	Medium	Low	20.9	6.4	Medium and growing. Technological enhancements. Stiff competition.
Cellular handsets	Large	Very low	69.5	18.1	Small and growing rapidly. Highly emergent technology. Many entrants.
Personal computers	Medium	Very low	35.0	17.4	Small and growing rapidly. Highly segmented. Emergent technology. Stiff competition.

Source: Srivastava and Srivastava [32].

comprising three interconnected strategies: pollution prevention, product stewardship and sustainable development along with their corresponding driving forces, key resource requirements and their contributions to sustained competitive advantage. Bloemhof-Ruwaard et al. [2] elaborate on the possibilities of incorporating green issues when analyzing industrial supply chains and more generally of the value of using Operations Research (OR) models and techniques in GrSCM research.

Coming to RL, it is the collective noun for logistic environments related to reuse of products and materials. Possible cost reductions, more rigid environmental legislations and increasing environmental concerns of consumers have led to increasing attention to RL in the recent past [4]. The existence, effectiveness, and efficiency of service management activities such as repair services and value recovery depend heavily on effective RL operations [7]. Rogers and Tibben-Lembke [9] define RL as... *the process of planning*, *implementing* *and controlling the efficient*, *cost-effective flow of raw materials*, *in-process inventory*, *finished goods and related information from the point of consumption to the point of origin for the purpose of recapturing or creating value*, *or for proper disposal*. Therefore, designing effective and efficient RL networks is a pre-requisite for repair and remanufacturing and a key driver for providing the economic benefits necessary to initiate and sustain GrSCM initiatives on a large scale [4].

RL has been used in many applications like photocopiers [1], cellular telephones [10], refillable containers [11], etc. In all these cases, one of the major concerns is to assess whether or not the recovery of used products is economically more attractive than disposal. The added value could be attributed to improved customer service leading to increased customer retention and sales. The added value could also be through managing product returns in a more cost effective manner [12] or due to a new business model [13].

Until recently, RL was not given a great deal of attention in organizations. Many of them are presently in the process of discovering that improving their logistics processes can be a value-adding proposition that can be used to gain a competitive advantage. In fact, implementing RL programs to reduce, reuse, and recycle wastes from distribution and other processes produces tangible and intangible value and can lead to better corporate image [14]. RL is one of the five key activities for establishing a reverse supply chain [15] and comprises network design with aspects of product acquisition and remanufacturing [16]. Literature identifies collection, inspection/sorting, pre-processing and logistics & distribution network design as four important functional aspects in RL. In many cases, RL networks are not set up independently 'from scratch' but are intertwined with existing logistics structures. Fig. 2 shows the basic flow diagram of RL activities where the complexity of operations and the value recovered increase from bottom left to top right.

RL can have both a positive and a negative effect on a firm's cash flow and needs further research attention [13,17]. Organizations and supply chains need to understand the financial impact of RL strategies which can generate periodic negative cash flows that are difficult to predict and account for. Toktay et al. [18] find that end-of-use returns have the potential of generating monetary benefits. Horvath et al. [17] use a markov chain approach to model the expectations, risks, and potential shocks associated with cash flows stemming from retail RL activities and actions for avoiding liquidity problems stemming from these activities.

A number of risks and uncertainties are associated with end-of-use recovery. These are related to timing, quality, quantity and variety of returns; estimation of operation and cost related parameters for RL networks; decisions about resolution for product returns and costs of co-ordination along the reverse supply chain. These also depend on consumer behavior and preferences. Various incentives/disincentives to consumers based on product model and product quality can influence the quality and quantity of product returns [19]. Therefore, RL operations and the supply chains they support are significantly more complex than traditional manufacturing supply chains [7,9,20]. So, just as companies develop efficient logistics processes for new goods, they must do the same for returned goods, understanding that the processes may be quite different from those defined for forward distribution [21].

Fleischmann et al. [22] suggest that buy-back may lead to higher returns leading to economies of scale. Jayaraman et al. [23] have used resolution to customers for this. Offering differentiated take-back prices to consumers based on product model and product quality or charging a return fee is likely to reduce both the number of returns as well as its variance [19]. Mont et al. [13] present a new business model based on leasing prams where the product–service system includes the organization of a RL system with different levels of refurbishment and remanufacturing of prams, partially by retailers. They focus on reducing costs for reconditioning, reduction of time and effort for the same and finally on environmentally superior solutions.

Quantitative methods to support return handling decisions barely exist [5]. Most quantitative models in RL literature deal with production planning and inventory control in remanufacturing, facility location, resource allocation and flows [4]. The dimensions used to characterize the RL environments are returns volume, returns timing, returns quality (grade), product complexity, testing and evaluation complexity and remanufacturing complexity. Fleischmann et al. [16] provide a good review of quantitative RL models. Fleischmann et al. [24] give a theoretical investigation of the synergy between the forward and the reverse chain. Various modeling aspects relevant for designing RL networks such as types of problem formulations, various decision variables and parameters used, data collection and generation techniques and various solution techniques [10,22,23,25,26] can be seen in literature. These resemble multi-level warehouse location problems and present deterministic integer programming models to determine the location and capacities of RL facilities.

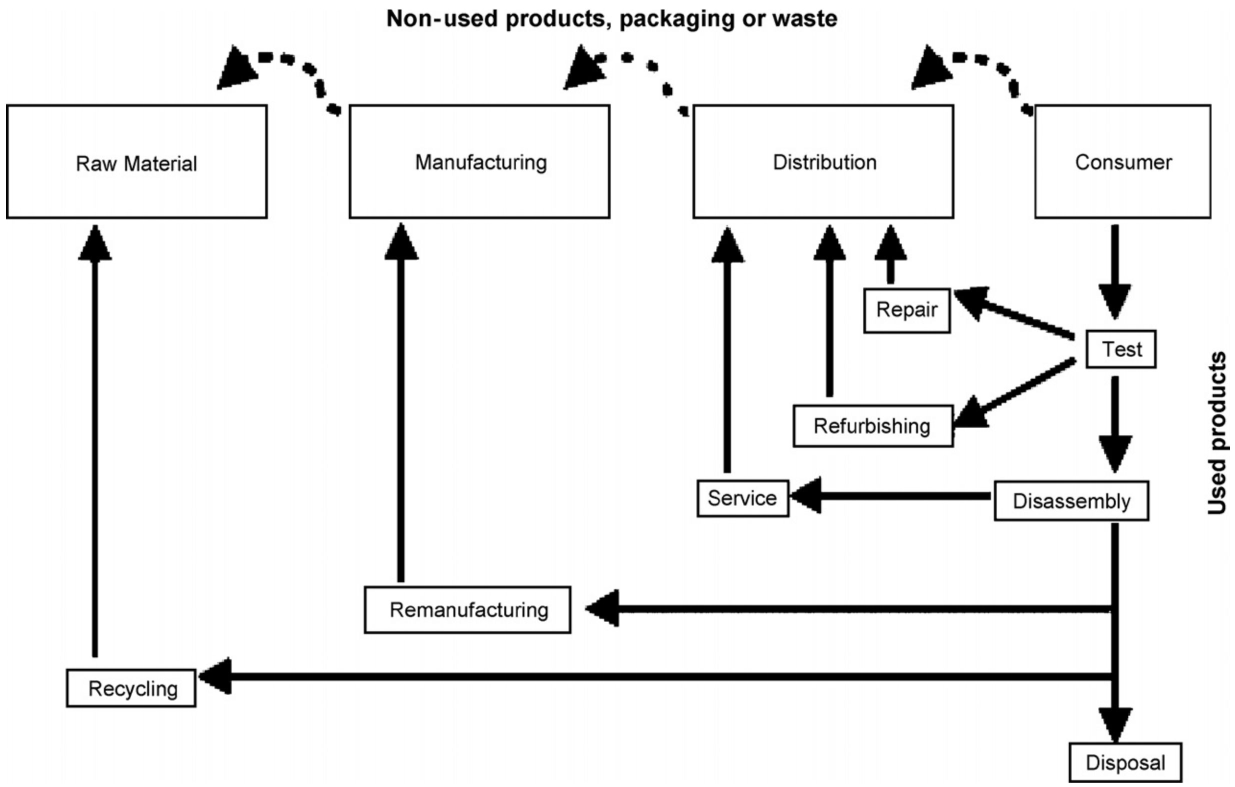

Fig. 2. Basic flow diagram of reverse logistics activities.

Uncertainty is not included explicitly in literature, but usually addressed via scenario and parametric analysis. Stochastic approaches are not much developed. Models do not incorporate multiple time periods although the same has been suggested as possible extension and future work [10,22,27]. Decisions may be long-term such as those about facility location, layout, capacity and design; or medium term such as those related to integrating operations or deciding about which information and communication technologies (ICT) systems are to support the return handling, which information is to be kept and for how long? Short-term decisions are related to inventory handling, vehicle routing, remanufacturing scheduling, etc.

Fleischmann et al. [22] consider the robustness issue of RL networks. They do so at two levels: at methodological level by examining the appropriateness of standard network design tools in a product recovery context and at topological level by analyzing the impact of product recovery on the physical network structure. As a basis for analysis, Fleischmann et al. [24] refer to a survey comparing nine case studies on recovery networks in different industries including carpet recycling [26], reusable packages [25] and electronics remanufacturing [10]. They conclude that the influence of product recovery is very much context dependent. Fleischmann et al. [28] find that the return flow information required by proposed models consists of the aggregate return volume in each period over the planning horizon. Toktay et al. [18] state that there are few documented business examples of forecasting specifically for RL. If one could exactly know how much is going to be returned and when, one would benefit from incorporating this perfect information *a priori* in the management of returns. de Brito and van der Laan [29] report on the impact of misinformation on forecasting performance and performance with respect to inventory costs by analyzing four forecasting methods as proposed by Kelle and Silver [11]. They find that estimates of the return rate can be quite erroneous in practice. Again, whether RL network is open loop or closed loop depends on a host of factors. In general, open-loop systems are common in commodity-based industries and are usually characterized by the existence of a seconds' market [6]. Again, Mitra [30] says that quality level of these will draw different prices in the seconds' market The problem of choosing an appropriate reverse channel is addressed by Savaskan et al. [27].

So, from the literature, it emerges that RL is not a symmetric picture of forward distribution [16]. It is much more reactive (supply driven). It is difficult to estimate supply-related parameters such as the unit operational costs directly from reported statistical data. Hu et al. [31] use interviews with high-level decision makers of high-technology manufacturers for estimation of supply-related parameters for their RL cost minimization model for the treatment of hazardous wastes. The interviews included both open and closed-ended questions. The analytical results of the interview data are then aggregated to identify the unit operational costs and appear in the objective function and constraints of their model.

Despite the success of a few organizations such as *Grameen Bank* in Bangladesh and *Unilever* worldwide, most organizations continue to mistakenly assume that poor markets possess no value recovery opportunities and have yet to understand the possibilities of serving the markets they are used to ignoring. Coordination requirement of two markets (market for products made from virgin materials and market for products made from earlier-used products), supply uncertainty of returns and disposition task (further action to be taken on returns) are identified as major challenges in RL literature [24].

4. Conceptual model

To address some of the issues related to designing RL networks for product returns, we conceptualize a three-echelon (consumers' returns → collection centers → rework sites) multi-period RL and value recovery network model as shown in Fig. 3. We try to address a number of strategic and operational questions related to disposition, location, capacity and customer convenience using this conceptual model. The definitions used in this conceptual model are described in Appendix A.

In our conceptual model, we assume that the consumers are the sources of product returns, similar to some of the existing literature [15,23,25,32]. We assume that the RL and value recovery network is designed from scratch as a '*bring scheme*' i.e., the customers bring the used product to collection/buy-back center (generally in a given time-window known a priori by telephone/Internet). For simplicity, we restrict the choice to the existing distribution/retail outlets, some or all of which may act as prospective collection center [32].

Further, the differentiated complexity of operations leads to two distinct rework sites: repair and refurbishing centers and remanufacturing centers. Repair and refurbishing centers require lower capital investment, are more skill-based and repair/refurbish goods in order to make them almost as good as new. Remanufacturing centers require very high capital investment, are more technology-based and produce upgraded remanufactured goods. The rework facilities will come up at some or all of collection centers. The disposition decisions are guided by profit motive and all the returned goods are resold in primary or seconds' market after necessary disposition. The first disposition (sell directly without rework) is carried out at collection centers themselves, as this involves no substantial investment [32].

As customers do not prefer long distances, the collection centers need to be located within a certain maximum distance from them. The customers receive a resolution price on acceptance of the return. We assume no take-back obligation. Testing facilities and product valuation charts are available at all collection centers. Manpower is skilled for inspection and testing.

We use data from Srivastava and Srivastava [32] for prospective locations of collection centers (a finite set model comprising 117 locations) as well as quality (grades), quantity and arrival-rates for three scenarios of product returns for select product categories for next 10 years in the Indian context. We also use informal interviews with various stakeholders and secondary data sources for estimating other input parameters such as costs, distances, processing times, and conversion factors (including recovery rates) associated with the activities shown in Fig. 3. We assume unconstrained storage capacity at each facility and negligible disposal costs. The capabilities and capacities of rework sites differ. Discrete capacity expansions are carried out at these locations. No trans-shipment is allowed among rework sites. A fraction of products sent to rework facilities cannot be remanufactured/refurbished. Modules are recovered from these and sold in primary or second's markets. Each product may have a few different type of modules (some of them may be common).

As reworked goods supply is much less than their demand in the current Indian scenario, we assume that the market for reworked products is unlimited. So, there is no closing/decommissioning of facilities. We also assume that price of various products and modules in primary and seconds' markets is known and suitable ICT infrastructure is in place to support, analyze and coordinate RL activities.

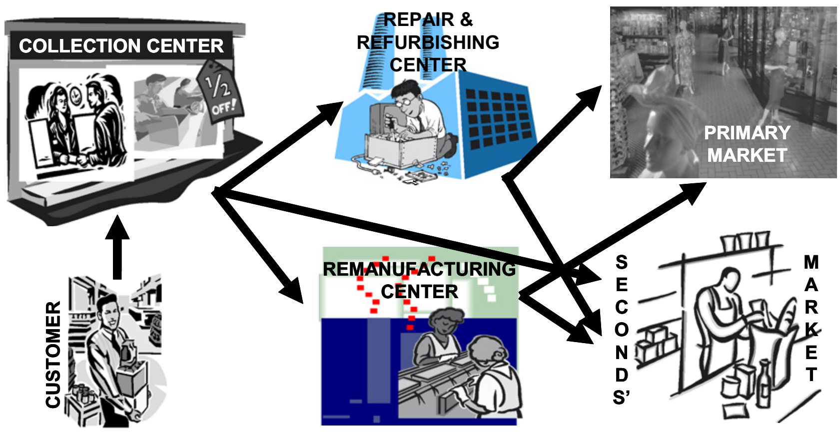

Fig. 3. The conceptual reverse logistics model.

5. Mathematical model formulation

We formulate a multi-product, multi-echelon, profit maximizing RL and value recovery network model covering activities from collection to first stage of remanufacturing. We ensure that it is a good representation of the real-life situation and is at the same time tractable. The objective function and various parameters and constraints have been clearly defined. The problem has been treated similar to a multi-stage resource allocation problem. Various decisions such as the disposition decisions, the sites to be opened, the capacity additions at any period of time as well as the number of products of a particular grade that are to be processed or sold during a particular period of time are decided by the model.

Our combinatorial problem resembles a multi-commodity network flow problem with a few sequentially dependent decisions for which no special algorithms are applicable apart from decomposition [33]. Besides, the large numbers of horizontal dimensions (117 probable candidate collection center locations) make our model very complex. For this, even for a single time-period, there are as many as 1.66×10^{35} $(2^{117} - 1)$ ways to open collection centers and 13 572 $({}^{117}P_2)$ possible routings of returns. The problem complexity and size force us to device a simple strategy that reduces computational complexity without any appreciable loss in the solution from practical perspectives. We find that there is no contradiction to our conceptual model, if the opening decision for collection centers is taken in a simple optimization model (based on certain strategic and customer convenience constraints) and thereafter impose these as rigid constraints for the main model that determines the disposition decisions, location and capacity addition decisions for rework sites (remanufacturing centers and repair and refurbishing centers) at different time periods as well as the flows to them from the collection centers.

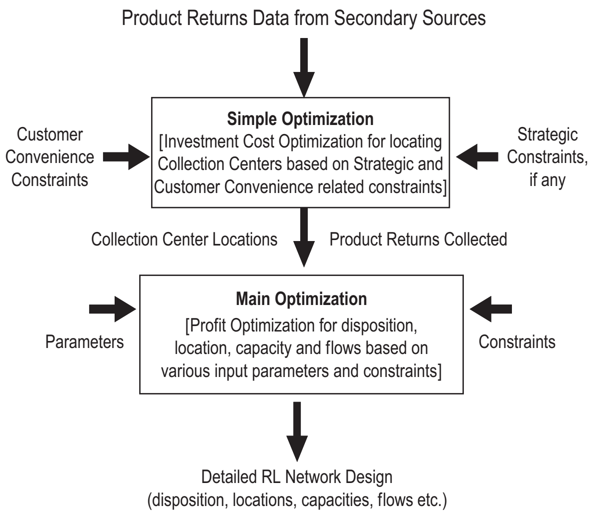

Fig. 4. Hierarchical optimization model.

Our hierarchical optimization model is shown in Fig. 4. The first optimization decides the collection center opening decision and all subsequent decisions are carried out by the second optimization. First, we use certain strategic and customer convenience constraints to determine the collection center locations. This model, coded in GAMS (general algebraic modeling system) also calculates the product returns at these locations. The main optimization model determines the disposition decisions; location and capacity addition decisions for rework sites (remanufacturing centers and repair and refurbishing centers) at different time periods as well as the flows to them from collection centers. The input parameters, variables and constraints have been derived on the basis of informal interviews with 84 stakeholders and the requirements of the mixed integer linear program (MILP) formulation based on the conceptual model.

The optimization model for collection center location decision minimizes investment (fixed and running costs of facilities as well as transportation costs) subject to following constraints:

(1) goods from a customer go to only open collection center,
(2) goods from a customer go to only one collection center,
(3) an open collection center remains open,
(4) distance between a customer and a collection center is within specified maximum limit to meet minimum customer service level requirements, and
(5) all parameters and variables are non-negative.

Number and grade of products originating at a particular customer zone during a particular time-period, distance between their origin and prospective collection centers, transportation cost for products per unit distance (borne by customer) and fixed and running costs of collection centers are some of the important input parameters used in this model. Maximum distance limit is set between origin of returns and their distance from collection centers for meeting customer convenience requirements. The binary decision variables decide whether a collection center is opened during a particular time-period and also ensure that a particular return goes to one open collection center only.

The main optimization model maximizes profit {realization from reselling − (RL costs + resolution price)}, subject to following constraints:

(1) the three disposition decisions are mutually exclusive and exhaustive,
(2) all goods with first disposition decision are resold at the collection centers,
(3) goods are sent to rework centers as per disposition norms,
(4) goods from collection centers go to only open rework centers,
(5) capacity balance at rework centers,
(6) goods processed within capacity limits at open rework centers,
(7) inventory balance at rework centers, and
(8) all parameters and variables are non-negative.

Here, realization from reselling is the sum of revenues from sale of returned products with or without rework as well as sale of recovered modules. RL costs comprise fixed and running costs of facilities, transportation, processing and inventory holding costs. The resolution price is the money paid to the customers for returns. Number and grade of products arriving at a particular collection center during a particular time-period, distance between collection centers and rework sites, transportation cost for products per unit distance, fixed and variable costs of rework centers, processing costs, processing times, capacity addition sizes and fraction of returns that can be successfully reworked on are some of the important input parameters used in this model. The binary decision variables decide whether capacity is added at a candidate rework center during a particular time-period. Other decision variables are related to disposition decision and various flows.

6. Data collection

For application of the proposed model, its input data may be classified into two groups: (1) returns data which include the types of returned products, and the time-varying amount associated with each type of product, and (2) operations and cost related parameters such as costs of facilities, capacity block sizes, processing times, fraction recovery rates, average number of recoverable modules, storage costs, processing costs, distances, transportation costs, procurement costs, sale prices and so on.

We take the product returns data from Srivastava and Srivastava [32]. These are shown in Table 2. For certain parameters such as collection costs and fixed and running costs of collection centers, informal interviews with various stakeholders are the main determinants. We decide the maximum distance a consumer won't mind traveling for returning a particular product by experimentation with the collection center model keeping in mind the consumer preferences from informal interviews. Fixed and variable costs of rework sites and the capacity sizes are based mostly on web-searches.

For most of other parameters, such as product grades, transportation costs, number of modules, sale price of modules, processing costs, resolution price paid, recovery rates, etc., we refer to secondary sources and arrive at some good estimates prior to approaching the stakeholders for deciding their values. Our interaction with stakeholders revealed that they use the resolution price as a reference for determining sale prices after disposition decision. Therefore, we use resolution price as the reference price for sale prices at various facilities.

Table 2
Relevant data for various product categories

Product category	Products in use in base year (in '000)	CAGR of forecasted sales (%)	Most likely estimated returns (in thousands)		
			1st Year	10th Year	CAGR (%)
Televisions	76 282	4.5	1254	6789	20.6
Passenger cars	5873	11.8	80	833	29.7
Refrigerators	26 104	9.7	498	3614	23.2
Washing M/C	4952	6.4	259	1690	24.6
Cellular handsets	2312	18.1	223	2474	30.7
Computers	5796	17.4	540	4760	27.4

Source: Srivastava and Srivastava [32].

Table 3
Few relevant operations and cost related parameters and their ranges

Items	Television	Refrigerator	Computer	Washing m/c	Car	Handset
Product grades	4	4	4	3	6	4
Transportation cost	0.6 (0.24)	0.4 (0.16)	0.3 (0.15)	0.5 (0.2)	1.0 (1.0)	0.1 (0.1)
Fixed cost (C)	400 000	300 000	300 000	300 000	2 400 000	180 000
Running cost (C)	1 200 000	600 000	300 000	600 000	2 400 000	180 000
Maximum distance (km)	300	200	250	200	200	150
No. of modules	3	10	15	4	30	3
Capacity block (R_m)	10 000 000	10 000 000	10 000 000	5 000 000 h	2 000 000 h	1 000 000
Capacity block (R_w)	500 000 h	2 000 000	50 000 h	200 000 h	100 000 h	50 000 h
Collection costs	50	80	40	40	200	20
Variable cost (R_m)	60 000k (6)	50 000k (5)	50 000k (5)	20 000k (4)	120 000k (60)	5000k (5)
Variable cost (R_w)	600k (1.2)	2000k (1.0)	100k (2)	200k (1)	20 000k (20)	50k (1)
Sale price (Modules)	150–2500	50–4000	50–4000	150–2000	100–14 000	50–1500
Fixed cost (R_m)	500 000 000	750 000 000	750 000 000	300 000 000	1 000 000 000	50 000 000
Fixed cost (R_w)	5 000 000	30 000 000	750 000	3 000 000	10 000 000	500 000
Processing costs (R_m)	320–2790	800–3790	1800–6680	1800–3700	13 790–35 650	800–4300
Processing costs (R_w)	150–260	500–3600	1000–6300	1500–3600	10 650–30 650	500–3900
Recovery rate (R_m)	0.9–0.99	0.8–0.9	0.80–0.97	0.94–0.99	0.94–0.99	0.81–0.99
Recovery rate (R_w)	0.9–0.98	0.82–0.97	0.80–0.99	0.93–0.98	0.96–1.00	0.85–0.98
Processing times (R_m)	2.91–3.24	1.71–3.54	1.00–1.24	1.01–1.42	5.71–11.91	0.21–0.45
Processing time (R_w)	1.21–1.48	1.01–2.28	1.12–2.14	0.92–1.44	6.71–10.41	0.22–0.50
Sale price ratio (C)	0.85–0.94	0.90–0.94	0.95–0.98	0.90–0.95	0.92–0.99	0.90–0.98
Sale price ratio (R_w)	1.10–2.48	1.12–2.82	1.07–2.05	1.5–5.08	1.08–1.46	1.05–4.30
Sale price ratio (R_m)	1.15–2.54	1.15–2.94	1.10–2.10	1.55–5.10	1.10–1.50	1.06–4.35
Resolution price paid	2210–8020	2010–10 020	6120–18 020	1000–6000	40 000–20 002	1250–1000

Some important operations and cost related parameters used for our experimentation and analysis are given in Table 3.In the table, times and capacities are in hours and costs are in Indian national rupees (INR) [One US $\$ \approx 45$ INR]. The transportation costs in brackets are the ones that have been considered for deciding collection center locations in the GAMS model. These are in INR/km. The costs in brackets are the per-unit variable costs for remanufacturing ('R_f') and refurbishing ('R_w'). Ranges for other parameters in the table give lower and upper values. Their distribution within the range is generally non-linear.

7. Results and discussion

In this section, we discuss the results of experimentation and analysis across the select category of products under various scenarios to gain insights into both the modeling and solution aspects of the RL and value recovery network design. Simultaneously, we present a few generalizations of results and their derived managerial implications.

First, we experiment with the collection center model to find out the impacts of various factors such as maximum distance limits for customer convenience,

Table 4
Experimentation with collection center model for personal computers

Estimated returns scenario	% Per unit transportation cost	Collection centers to be opened ($t1$–$t10$)					
		Maximum distance constraint (km)					
		100	150	200	300	500	None
Pessimistic	0	80	59	43	23	10	1
	20	80	59–60	43–47	23–27	10–15	10–12
	40	80	59–61	43–47	23–27	11–19	10–16
	60	80	59–61	43–48	23–27	11–19	11–25
	80	80–81	59–61	43–48	23–31	12–26	11–30
	100	80–82	59–62	43–48	23–35	12–30	11–30
Most likely	0	80	59	43	23	10	1
	20	80	60–63	46–48	26–35	15–31	11–31
	40	81	60–67	47–55	27–47	16–45	16–45
	60	80–83	63–72	49–64	28–63	19–60	16–60
	80	81–86	63–75	49–70	30–68	20–65	20–65
	100	82–85	63–76	49–72	33–69	20–67	20–67
Optimistic	0	80	59	43	23	10	1
	20	80	60–67	47–56	27–42	16–39	15–39
	40	80–85	63–74	49–68	30–66	20–64	20–64
	60	82–87	63–76	49–72	35–70	30–68	30–68
	80	82–91	64–83	51–80	39–77	34–76	33–76
	100	83–92	68–84	52–83	45–81	39–80	39–80

transportation costs and fixed and running costs, so as to arrive at reasonable parameter values that keep the model simple (in terms of size) and do not put any significant unrealistic constraints on the main model. As the transportation costs for bringing the returns to collection centers are borne by the customers, their maximum distance from consumers should be within reasonable convenient limits, inputs from informal interviews with various stakeholders about maximum distance limits are taken into consideration while designing the experiments. The results for one such experiment for PCs are shown in Table 4.

We see that for lower volumes and lower percentage per unit transportation costs, the maximum distance constraint is pre-dominant whereas percentage per unit transportation cost becomes more significant for higher distances. In absence of this constraint, the percentage per unit transportation cost is the only criterion and the number of collection centers opened increases progressively. It also increases with time as the number of returns increase with time. In absence of both, the model suggests opening just one collection center. Optimization for most likely returns with maximum distance limit in the range of 100–300 km and percentage per unit transportation cost in the range of 40–60% seems rational.

Next, we generate various scenarios with the optimization models using variations in processing times, processing costs, return rates and other sensitive and significant input parameters for our select categories of products. This helps us to draw some useful implications and managerial insights regarding characteristics of RL networks for these. Here, we do not present detailed results for different scenarios and present only a few significant results and interpretations derived from them in Table 5.

The disposition decisions are affected by a complex interplay of various input and cost-related parameters. Small changes in many input parameters and variables change the decisions but do not affect the overall profits appreciably. Thus, the profits for near-optimal policies fall within a narrow range. Very few goods are sold at a discount without rework. Refurbishing decision is the dominant decision. The relatively high fixed and running capital costs of remanufacturing facilities act against them vis-à-vis relatively cheaper and labor-intensive repair and refurbishing facilities. The facility sites keep on increasing with time period from year to year and are somewhat proportional to returns for a given maximum distance limit for customer convenience. Further, we see that the RL networks for refrigerators and televisions and the ones for cellular handsets

Table 5
Few significant decisions for the most likely scenarios

Decisions	TV	Car	Refrigerator	Washing M/c	Handset	Computer
Disposition 1 (resell)	0.6%	0.2%	0.5%	0.0%	0.0%	0.8%
Disposition 2 (remanufacture)	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Disposition 3 (refurbish)	99.4%	99.8%	99.5%	100.0%	100.0%	99.2%
No. of collection centers	49–68	11–40	21–37	34–47	52–72	26–44
No. of 'repair and refurbishment' centers	5–18	5–26	5–27	7–26	26–58	17–35

Table 6
Some significant outputs for different products

Context	Television	Cars	Refrigerators	Washing machines	Handsets	Computers
Profit (million INR) [most likely]	15 651	2173.1	881.0	220.2	732.7	193.9
Profit (million INR) [pessimistic]	3560	184.2	96.6	18.9	115.3	27.1
Profit (million INR) [optimistic]	33 222	4771.4	1763.9	451.1	1355.2	346.6
Break-even value [Inflexion point]	4%	6%	4%	17%	2%	6%
Avg. capacity utilization (W) [most likely]	24.3%	96.9%	22.9%	25.3%	65.1%	81.3%

Table 7
Average profit per returned item for most likely scenarios

Product category	Profit (million INR)	Returns ('000)	Average profit (INR)	Average resolution (INR)	% Avg. profit/avg. resolution (%)
TV (combined)	15 651	42 282	370	4766	8
Passenger cars	21 731	4151	5236	11 7664	4
Refrigerators	8810	19 761	446	5947	7
Washing M/C	2202	9685	227	1395	16
Cellular handsets	7327	81 470	90	4108	2
Computers	1939	21 086	92	11 513	1

and computers exhibit similar characteristics. These are different and distinct for the other two product categories, namely passenger cars and washing machines.

We also determine the absolute profits (in million of INR) for the three scenarios (most likely, pessimistic and optimistic) and the break-even values of returns for setting up various facilities for product returns for a 10-year period time-horizon. Average capacity utilization of the rework facilities for the most likely scenario is also calculated. These are shown in Table 6. All categories show profits even for the pessimistic scenarios. The break-even values for establishing value recovery from product returns for these product categories, except for washing machines, is quite low. Further, we observe that the average capacity utilization is higher for cars and computers and relatively lower for refrigerators and washing machines.

Stakeholders are interested in the average profit per item if appropriate RL network (as suggested by our approach) are set up. Table 7 summarizes results for the most likely scenarios. The average profit per item is quite high for passenger cars and fair enough for televisions, refrigerators and washing machines. The last column shows percentage of average profit per average resolution, a better indicator. These figures may be used for relating risk with returns. For example, the returns (as profits) for the 'risk-free' cellular handsets and computers are lower than that for the 'risky' washing machines. Other product categories lie in-between. Thus, setting up RL networks is profitable for all the select category of products; only the 'risks' and 'returns' differ.

The above discussions show that designing effective and efficient RL networks has important ramifications on OEMs and their consortia, local remanufacturers, third party service providers as well as markets. It may provide them many useful inputs and managerial insights (such as decisions regarding facility locations, dispositions and various flows as well as break-even values for investments and profits for a given scenario, etc.). By determining the factors that most influence a firm's RL undertakings, it can concentrate its limited resources in those areas; rest may be outsourced. The insights drawn from various scenarios help concerned stakeholders in identifying appropriate strategies. For example, for lower-grade used products of relatively high transportation effort, decentralization of facilities may be more successful.

8. Conclusions

This paper highlights and re-inforces the importance of RL—an important area for practitioners which has been under-explored by academics. We carry out RL and value recovery network optimization and explore the implications of setting up of *remanufacturing* and *repair and refurbishing* centers by OEMs or their consortia for certain categories of products in Indian context. The major contribution of this research lies in developing a formal framework for analyzing the network model and providing useful managerial insights. Experimentation with variations in processing times, processing costs and recovery rates provides insights for various decisions. Insights into implementation issues can be drawn and if necessary, the model may be modified (by using rigid constraints about various flows and facility opening decisions) for further analysis.

Our model determines the disposition decision for various grades of different products simultaneously with location–allocation and capacity decisions for facilities for a time horizon of 10 years. We develop our conceptual model from scratch borrowing from existing literature and industry practices and model the problem in an operations research (OR) framework. We use a bi-level program with decomposition to solve our profit maximization problem. Williams [33] suggests that a good model can be developed by focusing on ease of understanding, ease of detecting errors and ease of computing the solution. We do the same. The basic problem is formulated as a Mixed Integer Linear Program (MILP). We use GAMS 21.2 with full version of the CPLEX 7.5 Solver. We use informal interviews with various stakeholders, similar to Hu et al. [31] for estimating various operational parameters and justify the tools used and explain methodology for estimation of parameters.

As in the existing literature, we find a significant impact of quantity, quality and timing of returns on decisions as well as overall profit [22,28]. There is space and time dependency of various decisions, which is in agreement with the basic rationale behind our approach. The customer convenience distance constraints and the per unit transportation costs also impact the network design to a considerable extent. Further, we find that data assumptions have direct implications on the construction of the underlying scenario.

Our work is a first step towards RL network design for product returns and value recovery in the Indian context. It has been able to highlight various risks and opportunities. The findings show that presently remanufacturing is not a viable economic proposition. Underdeveloped remanufacturing technologies and high capital investment in remanufacturing facilities are the bottlenecks. Besides, product returns in most categories are still lower than the scale of operations needed to reach the ‘critical mass’ to make remanufacturing economically viable.

Kroon and Vrijens [25] consider wide domain of GrSCM in a simple context of recycling of empty containers. Jayaraman et al. [10] consider remanufacturing costs per unit and storage limitations of facilities in their closed loop supply chain model. Jayaraman et al. [23] consider remanufacturing facilities’ capacities in their RL model. Our model tries to take the work further covering a wider domain of GrSCM. It considers variables and parameters till the first stage of remanufacturing while optimizing facilities design. The model decides even the disposition decision for a particular grade of product at a particular location during a particular period of time. Thus, it integrates RL and value recovery. There are instances in literature [10,22] suggesting multi-period models as avenues for future work. Hu et al. [31] have used multi-time period models in slightly different contexts. We develop and experiment with a full-fledged multi-period model. It considers resolution price as well as sale of recovered modules. This is a step further to the consideration of revenue from sale of reclaimed material and similar to component recovery suggested by de Brito and Dekker [19]. We agree with Toktay et al. [18] that return flow parameters should be updated with time.

This paper has its own limitations. We deal with supply side (returns) and returns’ disposition but do not consider the co-ordination of the two markets. We still follow a “push” system where the volumes of returns drive the decisions and do not consider controlling product returns. The paper by Savaskan et al. [27] considers many of these issues explicitly, assuming closed loop supply structures as given. Thus, our work is complementary to their paper. We choose facilities from given location options; there is no free choice. During formulation, we carry trade-off between scope and utility, while in the solution we trade off between computation time and optimality. The MILP model assumes that only one block of capacity may be added during one time-interval at a prospective site. Again, as our model has a very big measure of time-period (1 year), we do not consider lead-times in transportation, as they are negligible with respect to a single time-period. We do not consider integrated logistics (forward and RL) in a single model. Further, we assume that all refurbished/remanufactured products can be sold (unconstrained market).

The cost of rework vis-à-vis cost of production from virgin materials too has not been considered. We carry out estimations and optimization for product categories and not brands or OEMs per se; however, inferences can be drawn for them by simply using percentage of returns equal to the market share of the brand or OEM. Finally, our approach is highly flexible and has scope for further enhancement and enlargement. It can easily incorporate multiple cost structures, market side considerations and constraints related to resource conservation and regulatory perspective. It may be used for other potential products such as tires and batteries. Similarly, though our study was done in the Indian context, it can be adapted and applied to situations in other developing countries.

The paper opens a number of avenues for future research such as considering integrated logistics—under which circumstances should returns be handled, stored, transported, processed jointly with forward flows and when should they be treated separately; comparing cost of remanufacturing with cost of production from virgin materials; potential attractiveness of postponement strategies in value recovery; changes in a firm's RL and value recovery strategy for a particular product over the course of the product's life; and modeling for situation when customer returns cannot be turned down.

The existing model may be configured for certain operational as well as strategic decisions to develop a customized decision support system. Penalties may be imposed in the model instead of rigid customer convenience distance constraint. More detailed aspects of remanufacturing too may be included. Assumptions such as unrestrained markets and infinite storage capacity may also be relaxed. Similarly, cost of remanufacturing vis-à-vis cost of production from virgin materials may be taken into consideration. Comparing/contrasting to similar issues in countries like Brazil, China, Japan, Mexico, Russia and USA, may throw light on how the demographic makeup impacts RL network design. Considering the co-ordination of the two markets offers another very rich and fertile avenue for future work.

Finally, we agree with de Brito and Dekker [19] that learning more about the practice of RL network design for product returns can complement some of the latent modeling difficulties. So, survey-based research methods may be used to explain current practices, predominant and critical issues and managerial techniques used to manage the RL networks. Again, empirical studies in other countries as mentioned above may be very useful. For example, research towards best practices may help decision makers to come up with solutions for various strategic, tactical and operational aspects. Simultaneous desk and field research will aid such decision-making.

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Appendix A. Definitions used in the conceptual model

Collection center: A facility where customers bring their products for resolution.

Disposition option: The decision about what is to be done next to the accepted returns. There are three types of disposition options: sell them without rework at the collection center; sell after repair and refurbishing; sell after remanufacturing.

Modules: Particular set of items (assembly/subassembly) that serve a particular purpose and may be used in generally more than one product category.

Primary market: Market for sale of new and premium goods.

Product category: The types of products along with their different models.

Product grade: The classification of various returned product categories based on their quality. It is a nominal measure of the condition of a returned product.

Recovery rate: Fraction of products for which product recovery is possible. Modules are recovered from them. The remaining fraction (1-recovery rate) is sold in primary or second's markets.

Remanufacturing center: A rework facility using advanced technology for processing returned products.

Repair and refurbishing center: A rework facility using appropriate level of technology and skills for repairing/refurbishing returned products.

Resolution price: Monetary value paid for a product return.

Reverse logistics (*RL*): The process of planning, implementing, and controlling the efficient, effective inbound flow, inspection and disposition of returned products and related information for the purpose of recovering value.

Rework center: A facility where returned products are refurbished/remanufactured. There are two types of such centers depending upon the disposition decision and the level of technology and skills for processing returns into final products: repair and refurbishing center and remanufacturing center.

Second's market: Market for sale of repaired and discounted goods.

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