DECISION SUPPORT USING MULTI-CRITERIA DECISION MAKING FOR REVERSE LOGISTICS NETWORKS

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Abstract

Logistics is a key enabler for growth of the retail commerce and product manufacturing industry, and is increasingly emerging as a differentiator in terms of customer service and satisfaction. The logistics sector specific to manufactured product retailing in India was valued at USD 0.46 billion in 2016 and is projected to witness a CAGR of nearly 45-48 per cent in the upcoming five years to reach USD 2.2 billion by 2020.

Reverse logistics has attained more and more pertinence during the recent years, as the economics and control over product returns is becoming far more crucial for industry, economy, and environment sustainability. Customers expect a seamless, economical and extended product usability, cost-efficient reuse thereof and safe disposal at its end-of-life. This focus leaves reverse logistics far more relevant in modern times.

Because of the fluctuation and uncertainty in both quantity and quality of the reverse product returns' flow, design and planning of reverse logistics network is much more complicated compared to the forward supply chain. Because of huge potentials and implications for acute optimization and seamless integration with the forward supply chain, it has necessitated focus on optimization of different entities/components of the reverse logistics components. This could be accomplished by development of decision support tools for designing reverse logistics network in an economically efficient and environment friendly manner.

This research work, largely set up in Indian perspective, develops a conceptual framework of multi-criteria decisions involved in reverse logistics network configurations, identifies sector-specific network configuration preferences and validates it through multi-sector industry survey. A sensitivity analysis that determines cross-overs of prioritization in network preference is also validated.

Further, a generic mathematical formulation using Mixed Integer Linear Programming is developed for a typical multi-stage, multi-facility revere logistic network set up. The formulation is then optimized for actual inter-facility returns' flow, distance, and pertinent costs data for an existing automobile tire manufacturing organization.

Lingo 14 optimization tool is used to obtain optimized returns quantities, total costs, and decision support on numbers and locations for the facilities at each stage. Sensitivity to rise in quantity of returns is also evaluated and optimized.

State of the art of the research topic

As McIntyre of HP puts it, the primary output of today's production processes is waste. Across all industries, less than 10% of everything that is extracted from the earth (by weight) becomes usable products. The remaining 90% becomes waste from production. The biggest challenge manufacturing industries face today is to stretch this for socio-economic advantage.

The size of logistics sector in India is said to be $90 to $125 billion. The supply chain industry is growing at a rate of 15% per annum. India has jumped to 35th number in 2016 from 54th on logistics performance index (World Bank's biennial measures on SC Performance).

Key drivers have been:

- Make in India, Infra Investment associated with ports, Airports, Domestic demand growth, and increased trade
- Consumer requirement of seamless shopping experience with integrated reverse logistics mechanism
- Surge in practises for commercial value creation and retention

The economics and control over product return is far more complicated than that of the forward flow, for, reverse supply chain is generally not as much profitable as that of a forward supply chain. Contributing factors to this could be uncertainty over capacity utilization of transport facility and inexactness of forecast of requirements at various facilities in the reverse supply chain. Another aspect could be uncertainty over the quality variations of the returned products. Due to this, all the collected product returns cannot be re-manufactured or sometimes, more advanced operations are required for making the returned product resalable.

In recent years, Governmental and non-governmental organizations (NGOs) have been vouching the manufacturers to improve their environmental performance by integrating safe disposal and environment-friendly practices into reverse supply chain. Also, fast growing economies like India observe a large and growing market for economic extension of product life through reuse and thereafter, a safe disposal.

This necessitates bringing the total cost down so as not to let it eat through the business profitability. Optimum salvage of economic value for extended product life, and environment consideration and legislation are main drivers of design of modern day reverse logistics networks. Design and integration of reverse logistic network with the forward supply chain has become a key thrust area in order to be a cost-effective product/service provider.

In the present work, key reverse supply chain constituents contributing to sector-specific network have been examined through industrial survey for both types of product returns: end-of-life; and end-of-economic use. Further, the determination of the number and location of different facilities like collection centres, re-manufacturing centres, disassembly centres, recycling centres, disposal centres is demonstrated through real-field data of returns-flow and transportation costs of the products, components and materials between each stage in the network and also for the intra-stage quantity-flow between facilities in the reverse supply chain.

Definition of the Problem

Most contemporary manufacturing and distribution companies are investing a huge sum in processes, tools and resources to achieve seamless integration and operational efficiency in composite forward and reverse supply chain planning. They strive for integrated planning with the objective of increased customer service level, cost- responsiveness, and retention of proprietary knowledge to stretch value creation for an extended life.

The key issues related to a company's ultimate objectives have been addressed in this work, as under:

- Prioritization of objectives from the multiple objectives present, and identification of crossover points through sensitivity analysis, through extensive multi-sector industry feedbacks
- Mathematically model a typical generic reverse logistic network involving all entities with an optimization objective
- Determination of the number and location of different facilities to be established in the network and the quantity of flow of products, components and materials between each stage of the supply chain.

Objective and Scope of work

- Identifying key components and multi-criteria for reverse logistics networks through multi-sector industry survey, with a view to analyse the trade-offs inherent in reverse logistics network design and to evaluate the impacts of uncertainty on network design, through extensive industry feedback.

- Presentation of industry sector-independent mathematical formulation that involves optimization of various components of the reverse logistics network through mathematical modelling

- Testing the formulation through optimization software for real-life industrial case, and establish values for key decision entities, and also, decision support for facilities creation or otherwise.

Research gaps and original contribution by the work

A multi-industry survey of 10 different prominent and diverse industrial sectors engaged in for reverse logistics activities in and around NCR and the state of UP, Gujarat, and industrial zone of Pune has been used for configuration of physical reverse logistics networks for both types of product returns: end-of-life; and end-of-economic use has been shown.
Following research gaps emanate out of the literature survey:

- *While available quantitative models describe determination of detailed network layouts, they don't map conceptual framework with validation through sector-independent industrial data.*

Present work addresses this gap through multi-sector multi-industry industrial survey to suffice the sync. A generic model that could be customized for specific industry domain is developed.

- *The proposed models considered few elements of return and/or demand uncertainty, but have left out prioritization of objectives (Cross-over)*

Sensitivity to the multi-objectives has been analysed in this work in order to incorporate the cross-over objectives through prioritization.

- *Very few researchers have addressed the issue of development of a general framework for the network design. Most of the works in this area are limited to either a single type of product return (e.g. end-of-life) or a single type of recovery option (e.g. remanufacturing).*

  In this study, simultaneous incorporation of two types of product returns have been considered: end-of-life; and end-of-use.

- *Available literature doesn't offer a decision support model for defining framework of key reverse logistics entities and their key parameters. This is observed as crucial gap by the* *industry engaged in reverse logistics activities, and look to optimize the total cost of reverse logistics.*

This research gap has been extensively addressed in the present work. Moreover, the work also considers fluctuation (discrete rise) in number of incoming returns in determining the numbers and location of facilities for returns' processing.

The work, while predominantly set up in Indian perspective and geography, attempts to build a model that can be replicated to similar sector.

Methodology of Research, Results / Comparisons

To meet the objectives defined for this work, work has been carried out in the sequence as under:

1. Build-up of conceptual framework through determination of industry sector-independent business objectives and sub-objectives thereof, pertinent to reverse logistics activity and returns' management as a whole. Subsequently, determination of alternatives exercised by the industries for carrying out reverse logistics activity at each stages.

2. AHP modelling for prioritization of alternatives based on industry-responses, and establishment of preferences for alternatives by different sectors, using AHP Excel Solver, based on Saaty's (linear) scale.

3. Validation of the framework for three different industrial sectors and sensitivity analysis.

4. Mixed-Integer Linear Programming formulation of a generalised multi-stage reverse supply chain with an objective of Minimising the total cost for the reverse supply chain, comprising of transportation cost, processing cost, fixed facility cost and disposal cost, with analysis of entities under different situations, for entities comprising of :

    a. Customer zones,
    b. Collection centres,
    c. Remanufacturing centres,
    d. Disassembly centres,
    e. Recycling centres,
    f. Disposal centres,
    g. Primary markets and secondary markets.

5. The problem instances solved using Lingo 14 (Optimization Modelling Software for Linear, Nonlinear, and Integer Programming) on a computer with Intel Core 2 Duo processor of 2.10 GHz speed and 2 GB RAM.

Analysis of the work done

Stage-1: Identification of frameworks for reverse logistics networks and validation

- An industrial feedback from the following domains of industries engaged in reverse logistics was obtained to classify configuration preferences for three main reverse logistics decisions as:
    - Proprietary collection of returns v/s TPL partnered collection (P vs. T)
    - Centralized sort-testing v/s Distributed sort-testing of returns (C vs. D)
    - Processing at original facility v/s at secondary facility (O vs. S)

248 industries operating in reverse logistics in and around NCR and UP, Pune, and in Gujarat state of India, were surveyed, for establishing their preferred method of managing their returns, of which, 197 industries responded. We tabulate the responding sectors of industries in Table 1 below.

Table 2 displays summary of associated reasoning/consideration expressed by these industries operating in varied reverse logistic activity, for preferring particular choice/mode for carrying out activities at three-stages. As shown, each stage offers two alternatives, each having own merit, and responding industry opts for either of the alternatives. In some cases, industries also indicated use of a mixed-mode for particular return-variety, but for the purposes of simplicity, this work ignores such instances.

TABLE 1. Broad domains of responding industries

Industry domain
Paper and packaging
Rubber and tire (Butyl, Granules, Liquid Latex)
Plastic (Polypropylene Terephthalate-PET, PVC, Low density Polyethylene- LDPE, Acrylonitrile butadiene styrene (ABS), Polypropylene)
Automobile (Industrial, Passenger, farm)
Building material
Bottling (LPG, Soft drinks)
DC Batteries

Toner and cartridge
Electronic parts (Incl. Cellphones, Toys, ICs)
Apparel & other on-line merchandize

TABLE 2. Summary of considerations for alternatives by the industry respondents

	Alternatives for the network design	**Considerations**
Returns' Collection	Producer- managed (P)	• Maximizes the producers' control • Protects trade-secrets • Provides better opportunities to maintain rapport with end customer
	Third-party/ Industry (T)	• Preferable for consumer products operating in high volumes • Potential for cost sharing
Returns' scrutiny & classification	Central- location (C)	• Preferable for specialized and expensive sort-test • Preferable for consumer products operating in high volumes • Opportunity to share transport means used for forward supply chain
	De-centralised location (D)	• Preferred for simple testing infrastructure requirements • Reduced transportation for shipping scrap, resulting in reduced costs • Can adopt TPL partner
Returns' processing	Original facility processing (O)	• Makes sharing of installed facility possible • Better control over remanufacturing/reprocessing/recycle • Saves cost of establishing separate
	Secondary facility processing (S)	• Preferable for consumer products operating in high volumes • Potential for cost sharing with other similar producers • Frees original facilities from complicating processing schedules

Table 3 provides statistics of identified network configuration preferences classified and synthesized on the basis of industry responses obtained for the survey.

TABLE 0. Response statistics

	Preference (Sector-independent)	**No. of Responses**	**%**
1	P,C,O	13	6.6 %
2	P,C,S	19	9.6 %
3	P,D,O	17	8.6 %
4	P,D,S	15	7.6 %
5	T,C,O	35	17.8 %
6	T,C,S	34	17.25 %
7	T,D,O	31	15.74 %
8	T,D,S	33	16.75 %

Validation through AHP decision making model

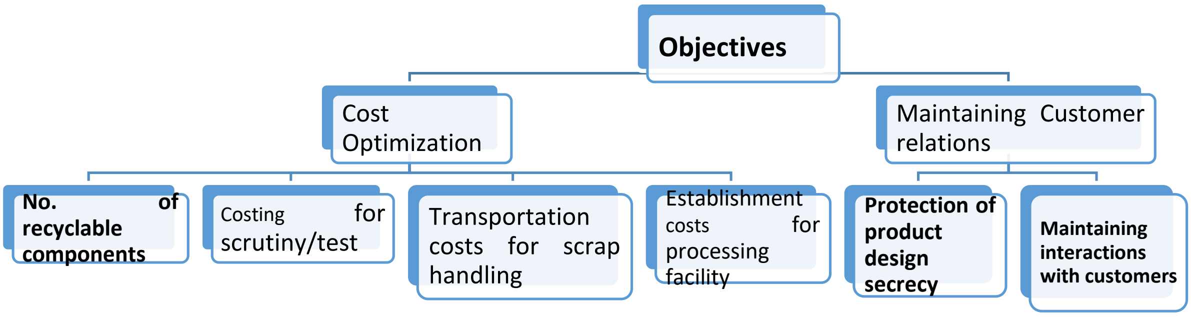

Fig. 1 Objectives, Sub-objectives and alternative associated

In the AHP analysis, two objectives for cost optimization and maintaining customer relations were associated with sub-objectives. Cost optimization objective was of sub-classified in to four sub-objectives as

- Number of Recyclable components in product returns
- Costing for scrutiny/test
- Transportation costs for scrap handling
- Establishment costs for processing facility

Similarly, maintenance of customer relation objective was sub-classified in to sub-objectives

- Protection of product design secrecy
- Maintaining interactions with customers

The eight network configurations identified as per Table 3 earlier were priority ranked for these sub-objectives by the industries using AHP, to yield sector-specific order ranking. AHP Excel solver was used to derive percentage priority rankings.

Table 4 below show the sectorwise rankings:

TABLE 4. Network configurations for different industry-sectors engaged in RL

Industry sector	Network configurations
Automobile manufacture (Industrial, Passenger, farm)	Produ. managed coll. (P), Central- location s & c (C), and Original facility proc.(O)
Rubber and tire (Butyl, Granules, Liquid Latex)	Produ. managed coll. (P), Central- location s & c (C), Seco. Fac. Proc. (S)
Electronic parts/ Electronic gadgets repair/refurbishment (Incl. Cellphones, Toys, ICs)	Produ. Managed coll. (P), De-Cent. Loc. S & C (D), Original facility proc.(O)
Toner and cartridge, Bottling (LPG, Soft drinks)	Produ. Managed coll. (P), De-Cent. Loc. S & C (D), Seco. Fac. Proc. (S)

Industry sector	Network configurations
Apparel & other on-line merchandize	TP Coll. (T), Central- location s & c (C), and Original facility proc.(O)
Plastic (Polypropylene Terephthalate-PET, PVC, Low density Polyethylene- LDPE, Acrylonitrile butadiene styrene (ABS), Polypropylene)	TP Coll. (T), Central- location s & c (C), Seco. Fac. Proc. (S)
DC Batteries	TP Coll. (T), De-Cent. Loc. S & C (D), Original facility proc.(O)
Paper and packaging, Building material	TP Coll. (T), De-Cent. Loc. S & C (D), Seco. Fac. Proc. (S)

We further analyze three cases that represent three key attributes of reverse logistics and returns' management: Remanufacturing, recycling and/or disposal thereof, and repair/refurbishment. The case studies are taken from actual reverse logistics systems, and they are: (1) Tire and rubber remanufacturing (2) Paper and paper product recycling, and (3) Electronic gadget repair/refurbishing.

Table 5 shows the prioritized weights (on Saaty's scale) for objectives and sub-objectives in the case studies.

We further chart sensitivity by using Excel charts to plot the sensitivity to different objective and sub-objectives for three case studies. Sensitivity to objectives and sub-objectives is shown in the Table 6.

TABLE 5. Prioritized weights for objectives and sub-objectives in the case studies

Objective/sub-objective	Tire and rubber products remanufacturing	Paper and paper products recycling	El. Gadgets repair and refurbishment
Cost optimization potentials	1	5	1
Customer relations	5	1	5
No. of recyclable components	3	6	3
Costing for scrutiny/test	4	2	2
Transportation costs for scrap handling	5	5	4
Establishment costs for processing facility	3	6	4
Protection of product design secrecy	5	1	5
Maintaining interactions with customers	5	1	7

TABLE 6. Sensitivity to objectives and sub-objectives for case studies

Objective/ Sub-objective	**Sensitivity**		
	Tire and rubber products remanufacturing	**Paper and paper boards**	**El. Gadgets**
Cost optimization objective	Slightly Sensitive	Sensitive	Sensitive
Customer relations objective	Insensitive	Sensitive	Slightly Sensitive
No. of recyclable components sub-objective	Insensitive	Sensitive	Insensitive
Costing for scrutiny/test sub-objective	Sensitive	Sensitive	Sensitive
Transportation costs for scrap handling sub-objective	Sensitive	Sensitive	Sensitive
Establishment costs for processing facility sub-objective	Insensitive	Sensitive	Insensitive

Stage-2: Mixed Integer Linear Programming formulation

Reverse supply chain, existing in NCR and UP industrial zones, consisting of five market clusters, seven locations for collection centers, three locations for remanufacturing centers, four locations for disassembly centers, three locations for recycling centers, one disposal center, two secondary markets and two primary markets are considered. The problem involves the determination of the number and location of different facilities to be established in the network and the quantity of flow of products, components and materials between each stage of the supply chain. The objective minimizes the total cost comprising of transportation cost, processing cost, fixed facility cost and disposal cost. The network is modelled and optimized using mixed-integer linear programming formulation with minor customizations that minimizes the total cost of the multi- stage reverse supply chain.

Formulation:

<u>Nomenclature:</u>

- Z set of market zones
- C set of collection centers
- R set of remanufacturing centers
- D set of disassembly centers
- L set of recycling centers
- M set of primary markets
- S set of secondary markets
- K set of disposal sites
- P products returned

- EU end-of-use products
- EL end-of-life products
- RC recyclable components
- DI disposable items
- RM recycled materials
- RP remanufactured products
- PRm returned product from customer zone m, m ∈ Z
- HCn handling cost per unit at collection center n, n ∈ C
- PC_i n processing cost of product, component or material per unit at facility n, where n∈R, D, L and I ∈ EU, EL, RC
- Ui unit cost of disposal of material i, where i∈ DI
- dmn distance between facilities m and n, where m, n ∈Z × C, C ×R, C ×D, R× S, D × L, D × K, L ×M tci Transportation cost per unit product/ component/material i
- fn fixed cost of facility n, where n∈ C, R, D, L
- Cap_i n capacity of facility n, for product/ component/material i
- ∝ maximum flow rate of the collected products to the remanufacturing centers
- b number of recyclable components produced from the product at disassembly center

Decision variables

- $X^i_{m;n}$ quantity of product/component/ material i shipped from facility m to facility n, where m, n ∈ Z× C, C× R, C× D, R× S, D × L, D × K, L ×M and i∈ P, EU, EL, RC, DI, RM, RP
- Y_C 0-1 variable, YC=1 if collection center C is used else Y_C=0
- Y_R 0-1 variable, YR =1 if remanufacturing center R is used else Y_R =0
- Y_D 0-1 variable, YD =1 if disassembly center D is used else Y_D =0
- Y_L 0-1 variable, YL =1 if recycling center L is used else Y_L =0

Objective function

The objective is to minimize the total cost of the multi- stage reverse supply chain. Minimize:

$$\sum m \in Z \sum_{n \in C} \sum_{i \in P} X_{mn}^{i} \times (tc_i \times d_{mn} + HC_n) + \sum_{m \in C} \sum_{n \in R} \sum_{i \in EU} X_{mn}^{i}$$
$$\times \left(tc_i \times d_{mn} \times PC_n^i\right) + \sum_{m \in C} \sum_{n \in D} \sum_{i \in EL} X_{mn}^{i} \times \left(tc_i \times d_{mn} \times PC_n^i\right)$$
$$+ \sum_{m \in R} \sum_{n \in S} \sum_{i \in RP} X_{mn}^{i} \times (tc_i \times d_{mn}) + \sum_{m \in D} \sum_{n \in L} \sum_{i \in RC} X_{mn}^{i} \times \left(tc_i \times d_{mn} + PC_n^i\right)$$
$$+ \sum_{m \in D} \sum_{n \in K} \sum_{i \in DI} X_{mn}^{i} \times \left(tc_i \times d_{mn} + U^i\right)$$
$$+ \sum_{m \in L} \sum_{n \in M} \sum_{i \in RM} X_{mn}^{i} \times \left(tc_i \times d_{mn}\right) \sum_{m \in C} f_m \times Y_m + \sum_{m \in R} f_m \times Y_m + \sum_{m \in D} f_m$$
$$\times Y_m + \sum_{m \in L} f_m$$
$$\times Y_m \tag{1}$$

Subject to

$$\sum_{n \in C} X_{mn} = PR_m \ , \forall m \in Z, \forall i \in P \tag{2}$$

$$\sum_{m \in Z} \sum_{i \in P} X_{mn}^{i} \times (1-\alpha) \leq X_{mn}^{j} \ \forall m \in C, \forall j \in EL \tag{3}$$

$$\sum_{m \in Z} \sum_{i \in P} X_{mn}^{i} = \sum_{m \in R} X_{nm}^{j} + \sum_{m \in D} X_{nm}^{j} \ , \forall n \in C, \forall j \in EU, EL \tag{4}$$

$$\sum_{m \in C} \sum_{i \in EU} X_{mn}^{i} = \sum_{m \in S} X_{nm}^{j} \ \forall n \in R, \forall j \in RC \tag{5}$$

$$\sum_{m \in C} \sum_{i \in EL} (b \times X_{mn}^{i}) = \sum_{m \in L} X_{nm}^{j} \ \forall n \in D, \forall j \in RC \tag{6}$$

$$\sum_{m \in C} \sum_{i \in EL} X_{mn}^{i} = \sum_{m \in K} X_{nm}^{j} \ \forall n \in D, \forall j \in DI \tag{7}$$

$$\sum_{m \in D} \sum_{i \in RC} X_{mn}^{i} = \sum_{m \in P} X_{nm}^{j} \ , \forall n \in L, \forall j \in RM \tag{8}$$

$$\sum_{m \in Z} X_{mn}^{i} \leq Cap_n^i \times Y_n , \forall n \in L, \forall j \in RM \tag{9}$$

$$\sum_{m \in C} X_{mn}^{i} \leq Cap_n^i \times Y_n , \forall n \in R, \forall i \in EU \tag{10}$$

$$\sum_{m \in C} X_{mn}^{i} \leq Cap_n^i \times Y_n \ \forall n \in D, \forall i \in EL \tag{11}$$

$$\sum_{m \in D} X_{mn}^{i} \leq Cap_{n}^{i} \times Y_{n} \; \forall n \in L, \forall i \in RC \quad (12)$$

Y_n is binary, $\forall n \in C, R, D, L$ (13)

$$X_{mn}^{i} \geq 0 \; and \; integer \; in \; product \; level \; flow, \forall m, n, and \; i \quad (14)$$

- The objective (1) minimizes the total cost of the supply chain consisting of the transportation cost between different facilities, processing cost at remanufacturing centers and recycling centers, handling and sorting cost at collection centers, disposal cost and fixed facility cost associated with different facilities.
- Constraints (2) to (8) ensure conservation of flow between different stages.
- Constraint (2) implies that all the products available at customer zones should be collected through different collection centers. Constraint (3) ensures that all the end-of-life products should go for disassembly operation.
- Constraint (4) represents the conservation of flow of collection centers.
- Constraint (5) represents the conservation of flow of remanufacturing centers.
- Constraint (6) implies that the total outflow from a disassembly center to all recycling centers is equal to the inflow of products into the disassembly center multiplied by the number of recyclable components produced from that product.
- Constraint (7) represents the conservation of flow of disposable items.
- Constraint (8) represents the conservation of flow of recycling centers.
- Constraints (9) to (12) show the capacity limitation of different facilities.
- Constraint (9) represents the capacity of collection centers. The total flow of returned products into a collection center should not exceed its capacity.
- Constraint (10) implies that the total reverse flow of products into a remanufacturing center should be less than or equal to its capacity.
- Constraint (11) implies that the total flow of returned products into a disassembly center should be less than or equal to its capacity.
- Constraint (12) implies that the total reverse flow of recyclable components into a recycling center should be less than or equal to its capacity.
- Constraint (13) represents the binary variables.
- Constraint (14) ensures the non-negative flow of products, components and materials.
- Also, the variables are restricted to an integer value, when the flow is in product level.

Stage-3: Optimization of the modelled formulation for real life industrial data for specific sector (Rubber Tire remanufacturing)

The next stage in logical sequence was to test the formulated reverse logistics optimization problem for a real life industry data. An industry sector that involves all typical entities of a reverse logistic flow was chosen for a representative data validation.

A reverse supply chain for the automobile (and farm tire manufacturing organization, which is a global player in tire manufacturing. The manufacturer has two manufacturing plants in India, and we limit our scope of study to the returns' management practices for its Ballabgarh plant in the district Faridabad in the state of Haryana. **Faridabad** is a leading industrial center and situated in the National Capital Region bordering the Indian capital New Delhi.

The manufacturer has exclusive arrangement for the returns' management. They have categorized returns coming from five market zones in Noida, Faridabad, Ghaziabad, Gurugram, and Sonipat.

The manufacturer has seven returns collection centers located at:

- Noida Phase-II
- Ajronda, in district Faridabad.
- Dasna in district Ghaziabad
- Manesar in Gurugram
- Dhankot in Gurugram
- Murthal in Sonipat, and
- Kakroi in Sonipat, Haryana

The manufacturer has facilities for sorting and pre-processing facilities at four locations, namely, Ajronda, Manesar, near Greater Noida, and near Dasna. From here, the returns head to either remanufacture/repair, recycle or disposal, as per the sorting scrutiny.

Three remanufacturing and repair facilities are located at the plant at Ballabgarh, Moradabad, and Bahadurgarh. Three recycling plants are located in the vicinity of Bulandshahar, Chhaprola, and in Yadavnagar in Ghaziabad. The company has disposal plant near Jewar.

Major chunk of its recycled tires go to primary markets in Gurugram and Ghaziabad, from where they are distributed for the primary market. Also, the repaired or remanufactured tires move to secondary market retail centers in Gurugram and Faridabad.

The actual distances between operational facilities were calculated using Google maps.

Input data was obtained for

- Number of product returns at different customer zones
- Inter-facility distance between
    - Customer zones- collection centers
    - Collection centers-Remanufacturing centers
    - Collection center- Disassembly centers
    - Remanufacturing centers- Secondary markets
    - Disassembly centers- Recycling centers
    - Disassembly centers- Disposal centers
    - Recycling centers- Primary markets
- Unit transportation cost for various returns-categories, such as
    - Returned products
    - End-of-usage products
    - End-of-economic life products
    - Remanufactured products
    - Recycled components
    - Disposable items
    - Recycled material
- Data for collection centers, Disassembly centers, remanufacturing centers, such as
    - Facility capacity
    - Fixed cost of facility set-up
    - Unit processing cost at facility

With these input data, key performance criteria, like total cost, transportation cost, Total fixed facility cost, Total processing cost, and Total disposal cost were evaluated.

The network design problem was then solved using Solver Lingo and the optimum design of the network was obtained. Major take-away of the work has been the decisions regarding the number and location of different facilities, and also, the optimized quantity of flow of products, components and materials between different stages.

Results (Abridged)

The input data was tested using the Lingo solver for branch and bound algorithm, and following decision support parameters were obtained.

R- 1) Cost components (in Rupee value) of the objective function

Key evaluation parameters (Optimized)	Money Value (in Rs.)
Total composite cost	14209720
Total cost of transportation	2379560
Total fixed cost (Facility establishment)	1722380
Total disposal cost	419880
Total processing cost	9687900

R- 2) Decision support for facility location selection decisions

Type of facility	Decision (Open at locations)
Collection centre	Noida, Ajronda, Dasna, Manesar, Dhankot
Disassembly centre	Ajronda, Manesar
Remanufacturing centre	Ballabgarh
Recycling centre	Bulandshahar, Ghaziabad

R- 3) We also obtained optimized flow of returns from market clusters to collection centers, Collection centers to pre-processing centers, Pre-processing centers to remanufacturing centers, and also disposal centers. The work was carried forward to determine costs, location decision and flow optimization for scenarios of 10 % and 20 % rise in quantum of returns.

Conclusion & future scope

Network design is the most critical area of reverse logistics that is assuming greater importance and interest of industry and researchers day by day. The present study has significant theoretical and practical implications in terms of the profitability of efforts, processes, environmental obligations, and economy of returns. The problem is solved for a realistic situation and a comparison of the solution under three different instances is also done. The results show the importance of the proper modelling and analysis of network design decisions.

The optimum solution obtained in one case may not be optimal in another situation with a tweak in terms of modality and capacity. The changes in the forecasted values of product return are inevitable. Hence, it is recommended that the decision makers should analyze the problem environment and its possible changes before taking a decision regarding the network design. The proposed model is a general one and with the proper analysis of the results obtained, it helps to analyze the long-term operation of a reverse supply chain. It can aid managers in taking better decisions for the network design of a reverse supply chain.

The model could be further extended for investigations under various scenarios and new emerging domains, like food processing and pharmaceutical returns, where the economy-loss would be staggering.

In this study, we considered only a single product, single-period situation and it could be further extended by considering a multi-product, multi-period situation. The uncertainty in data can also be incorporated into the study as a future research.

Moreover, inconsistencies in terms of re-manufacturability and quality assurance for re-manufactured products, especially in to booming sector like passenger automobiles, can be addressed by seeking solution through more formal and quantifiable routing and re-marketing problem. Researchers can build on the methodology adopted in this work, with necessary customization. The economic advantage achieved could be large.

It is, however, imperative to note here that the reverse logistics product return management is perennially considered a NP-Hard problem, and stochastic nature of the returns could affect and vary the expected outcomes. Different mathematical methods have been tried and tested by researchers to aid the network design decision makers, but the solutions advocated have still remained limited shelf-life solutions, and have been prone to turning pseudo-optimal or even non-optimal solutions.

Researchers have been moderately successful in proposing amicable solutions on optimal design of reverse logistics network configurations for specific product-ranges. However, future researchers can base their work on findings of this multi-sector industry study, and take it on from there to bring finesse and refinement in solution for specific sector they study. Also, it would be apt to stretch the solution-umbrella to similar and related products in the same industry-sector.

While the efforts have been made to include active industry-sectors into the scope of the study, still, our work only makes use of a few industries to ascertain its robustness of solution. Future research could study more industries to verify and further improve on the framework.

Finally, environment abiding disposal means and optimization of transportation -especially for the tire-manufacturing industry-sector discussed in the study- could help achieving the green supply chain in right vein. Researchers can base their future work on the present study and extend to other similar product returns having high environment impact.

Papers published and a list of all publications arising from the thesis

1. Chhaya UK, Dr. M.B. Patel; "*Validation of research design for multi-criteria decision support mechanism for reverse logistics networks*", 2012, International Journal of Scientific Computing Vol. 6; No. 2; 2012: ISSN: 0973-578X
2. Uday K. Chhaya, Dr. M.B. Patel ; "*Formulation and Validation of multi-objective decision support mechanism for reverse logistics networks";* Brown walker press Inc., USA*, 2013,* ISBN-10: 1612336248, ISBN-13: 9781612336244
3. Uday K. Chhaya; "Configuration of reverse logistics facilities networks for rubber and PET products: An industrial case study"; Sage Publications, Cogent Engineering OA journals, Taylor & Fransis; 2017; Under review
4. Uday K. Chhaya, Dr. M.B. Patel; "Network Configuration for Reverse logistics of product returns: An industrial case study"; International e-publication for International Science Community Association (Registered under Ministry of Corporate Affairs, Government of India) (www.isca.co.in); (ISBN number: **978-93-84659-77-6)**

Reviewed Conference publications:

1. Chhaya UK, Mankad AJ; "IT architecture for reverse logistics networks", International conference on Logistics & Supply Chain Management, Aug 3-5, 2004, Coimbatore

2. Chhaya UK, Mankad AJ; "*Virtual Networks for IT- Enabled Reverse Logistics Involving Decision Support for Supply Chain Management*"; International conference on Asia Pacific Industrial Engineering & Management System, Bangkok, Thailand; Dec 17-20, 2006, ISBN 974-8257-26-6

3. Chhaya UK,; "*Virtual networks in reverse supply chain & Logistics management: An IT architecture*"; International Conference on Advances in Manufacturing and Technology Management (ICAMTM 2007) Mumbai, India, January 2007

4. Chhaya UK, Mankad, AJ; "*Meta-Heuristics based model for decision support application of a reverse supply chain";* International conference on advances in Mechanical Engineering; SVNIT, Surat; Dec 15-17, 2008

5. Chhaya UK, Dr. M.B. Patel; "*Formulation and Validation of multi-objective decision support mechanism for reverse logistics networks";* International conference on

Emerging Trends in Mechanical Engineering*”;* Vallabh vidyanagar, 2013, ISBN: 978-1-61233-6244

6. Chhaya UK; Dr. M.B. Patel; “*Configuration of reverse logistics networks for rubber and PET products’ supply chain: An industrial case study”*; International conference on best practises in Supply chain management, Trivandrum, Dec 22-23, 2016

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