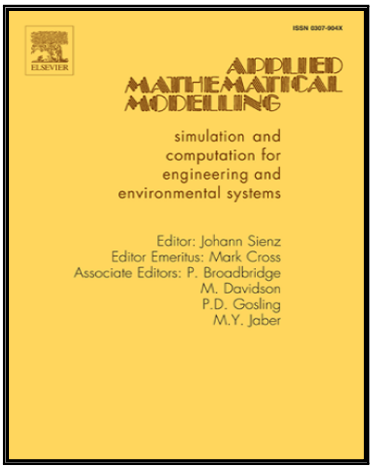

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**Highlights**

- Mathematical model that withstands variation in inputs over time
- Incorporation of bill of materials of the product into the mathematical model
- Simultaneous consideration of multiple recovery options
- Validation of the work with the design of a used refrigerator recovery network

# Multi-Period Reverse Logistics Network Design for Used Refrigerators

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## Abstract

This paper focuses on the design of a multi-stage reverse logistics network for product recovery. Different recovery options such as product remanufacturing, component repairing and material recycling are simultaneously considered. Initially, we propose a mixed integer linear programming model – with a profit maximization objective – for the network design problem. The structure of the product, by way of bill of materials (BOM), is also incorporated into the proposed model in order to analyze the flow at component and material levels. Sensitivity analysis is carried out to study the effects of variations in the values of the input parameters such as product return quantity, unit transportation cost per unit distance, and unit processing cost. The analysis shows that the design decisions of different facilities considerably change even for 5 to 20% variations in input parameter values. This led to the development of a refined mathematical model which incorporates variations in the different input parameter values over time. The new model provides a unified design for the entire planning horizon and has been validated with the design of a used refrigerator recovery network.

**Keywords:**

Reverse logistics, Network design, Remanufacturing, Repairing, Recycling, Refrigerator

## 1. Introduction

Reverse logistics deals with the collection and treatment of used products. Nowadays, apart from economic reasons, organizations across the globe are increasingly focusing on setting up reverse logistics networks owing to the adverse environmental effects caused due to the improper disposal of many used products. However, reverse logistics is still in a state of infancy, particularly in emerging economies (Bouzon et al., [1]). The economic potential associated with used products also makes research in this area quite attractive. According to the Environmental Protection Agency (Dat et al., [2]), there are 20–50 million metric tons of electronic waste (e-waste) alone generated worldwide every year.

Thus, organizations must consider the management of reverse logistics systems in addition to forward logistics (Tahirov et al., [3]; Govindan et al., [4]). Moreover, customers are becoming more knowledgeable about environmental pollution and this affects their purchasing decisions (Kara et al., [5]). So, having a proper mechanism in place for a reverse supply chain not only helps firms reduce the negative environmental impact of its used products but also enhances its green image in the markets it operates in (Pishvaee et al., [6, 7]). Original equipment manufacturers and third party logistics service providers often carry out the reverse logistics activities. Many companies such as Kodak, Xerox, HP, Dell and GM focus on remanufacturing and recovery activities, thereby achieving significant gains (Uster et al., [8]). Nevertheless, there are cases where organizations fail to achieve gains from recovery activities. For example, Ford, the automobile manufacturing firm, admitted that automotive recycling was a poor business decision (Karakayali et al., [9]).

One of the strategic decisions to be made in a reverse supply chain is the design of the network. This involves the determination of the number and location of facilities to be established. Typically, these facilities include collection centers, disassembly centers, remanufacturing centers, recycling centers etc. The design problem involves the determination of flow between different stages of the network. Reverse logistics activities involve additional supply chain costs which need to be managed. Different recovery options are associated with returned products. They can be remanufactured or the component parts can be repaired or recycled after disassembly. Remanufacturing brings the quality standards of used products up to that of new products (Thierry et al., [10]). Disposal of non-recyclable or hazardous materials is also a difficult task for organizations to carry out; but this too needs to be accomplished. In order to analyze product flows at the component and material levels, it is important to consider the product structure of the returned product by way of taking into account its bill of materials (BOM). Only a few studies have incorporated BOM of the product in the network design of a reverse supply chain (Dat et al., [2]; Alumur et al., [11]; Demirel et al., [12]; John et al., [70, 71]).

Abdallah et al., [13] observe that efficient design of a product recovery network is one of the challenges facing the emerging field of reverse logistics. This is partly due to the fact that forecasting the quantum of used product returns is relatively difficult compared to forecasting the demand for new products. Moreover, the network design thus obtained must be able to withstand changes in product returns over different periods of the planning horizon. Most network design studies on reverse logistics ignore this important aspect by considering a single period model rather than a multi period model.

Efficient reverse supply chains have to keep costs to a minimum. In this context, network design is a critical issue to be addressed. It consists of determining the number and location of facilities and establishing material flows between them. There is no universal “best” design for a reverse logistics network; each has to be tailored to the products involved and the economics of their reuse (Guide and Wassenhove [14, 15]).

In our study, firstly, a mixed integer linear programming model is proposed for the design of a reverse supply chain. The reverse supply chain consists of product return zones, collection centers, remanufacturing centers, dismantling centers, recycling centers, repair centers, primary markets, secondary markets and disposal centers. The model determines the number and location of different facilities to be established and the flow of different items in the supply chain. The grading of collected products at collection centers is based on the useful life remaining in the products; this aspect is also considered in our study.

In order to validate our model we design the reverse logistics network for used refrigerators. We then perform sensitivity analysis and on the basis of this, a refined mathematical model is proposed. The new model incorporates variations in the different input parameters over different periods of the supply chain and provides a unified design of the network over the entire planning horizon.

The important contributions of the paper are as follows:

- Formulation of a mathematical model which incorporates variations in the input parameter values over time; this provides a unified design for the entire planning horizon of the problem.
- Incorporation of bill of materials of the product into the mathematical model and consideration of recovery options such as product remanufacturing, component repairing and material recycling simultaneously in the supply chain.
- Analysis of the impact of variation of different input parameter values on the design decisions.
- Validation of the proposed model for the design of a used refrigerator recovery network.

The rest of the paper is organized as follows. Section 2 provides a review of the related literature on reverse logistics. Section 3 presents a description of the reverse logistics network design problem and the model formulation. Section 4 demonstrates the application of the proposed model for the design of a refrigerator recovery supply chain. Section 5 provides a refined mathematical model which incorporates variations in the input parameter values over time. This section also includes computational results and analysis. Section 6 lists the managerial implications of this work followed by conclusions in Section 7. The paper ends with identification of limitations and scope for further work in Section 8.

## 2. Literature review

Given the number of published studies available in the reverse logistics literature, it is simply not practical to review the whole of this literature here. Hence, we review select research papers pertinent to the problem of reverse logistics network design. In particular, we analyze the extent to which the features proposed in our work have been addressed in the literature. See Bei and Linyan [16], Aras et al., [17], Agrawal et al., [18], Govindan et al., [19] and Bazan et al., [20] for a comprehensive review of models and methods on reverse logistics and closed loop supply chains.

Network design decisions are strategic in nature because of the high costs associated with the opening (or shifting) of facilities and have long term ramifications on the performance of the supply chain. Typically when location decisions are made, the network configuration is expected to be stable throughout the planning horizon (set of time periods). This implies the dynamic nature of product returns in terms of the quantity and quality over several time periods has to be explicitly considered while designing a unified model. Melo et al., [21] review the literature and point out that approximately 82% of the surveyed papers deal with only a single period situation. There are only a few exceptions (Alumur et al., [11]; Realff et al., [22], Srivastava [23]; Zeballos et al., [24]) which incorporate the dynamic nature of the problem environment into the design problem. In all the cases except [11], the problem is solved in stages. The result obtained in the first stage is fixed and fed as an input to the second stage resulting in a sub-optimal approach. In [11] a multi-period model is considered. This uses time-indexed binary variables for capturing location decisions in an MILP model. This implies that the values of these variables can vary from one period to another period and hence the network configuration need not remain the same throughout the planning horizon. In reality, implementing such a solution is highly impractical because of the labor unrest associated with frequent hiring/firing policies. Moreover, opening and closing down facilities frequently may not be economical. This is an important research gap that our work intends to address. It is noteworthy that the model proposed in this work is applicable when the product return estimates are reasonably accurate for the planning horizon thereby making it a deterministic case. Refer to Listes and Dekker [25], Lieckens and Vandaele [26], Lee and Dong [27], Fonseca et al., [28] and Niknejad and Petrovic [29] for network models that incorporate stochastic factors. Specifically, Pishvaee et al., [30], Wang and Yuang [31] and Hatefi and Jolai [32] handle uncertainties in input parameters (such as customer demand, quantity and quality of product returns and facility disruptions). The authors successfully extend the concept of robust optimization theory for the design of closed-loop supply chain networks.

The different recovery options considered in the literature are: *remanufacturing*, *repairing* and *recycling*. Remanufacturing is the most widely adopted recovery option. Some of the studies assume that new products and remanufactured products can be used interchangeably for meeting the same customer demand. Jaber and El Saadany [33] state that this may not be true for many industries where customers do not consider new and remanufactured items as interchangeable. Gobbi et al., [34] state that the grade or quality of the returned product plays an important role in deciding the most suitable recovery option. The remaining useful life (RUL) is an appropriate measure of the grade of product return. Si et al., [35] define the RUL of an asset or a system as the length from the current time to the end of the useful life. RUL has an important role to play in maximizing the revenue generated; products with high RUL can be remanufactured and sold in a secondary market. Low RUL products have to undergo material and component level recovery (Gobbi et al., [34]). Some studies simplify the problem by considering only a single grade of product return and recovery (Hatefi and Jolai [32]; Eskandarpour et al., [36]) whereas some studies incorporate the grade of product return into the mathematical model by assigning weightages to each quality level (Dat et al., [2]; Roghanian and Pazhoheshfar [37]). In quite a few research studies, the life cycle stage of the returned product is considered as end-of-life (Demirel et al.,[12]; Ozkir and Basligil [38]; Suyabatmaz et al., [39]; Soleimani et al., [40]) The products in their end-of-life stage are technologically obsolete and often unusable. The only practical recovery alternatives for these products are parts recovery and recycling (Guide and Wassenhove [15]). In the present work, different recovery options such as product remanufacturing for higher grade products, component repairing and material recycling for lower grade products are considered simultaneously.

The objective of network design models can be either cost minimization or profit maximization. The results for these two objectives will be different if the revenue generated for the same item varies across markets. This is especially true in the case of emerging markets like India and China. In the literature, we observe that almost all the studies consider either a cost minimization (Jayaraman et al., [41]; Min et al., [42], Salema et al., [43]; Lee and Dong [27, 44]; Min and Ko [45]; Zhou and Wang [46], Lee et al., [47]; Mutha and Pokharel [48]; Grunow and Gobbi [49]; Easwaran and Uster [50, 51]; Diabat et al., [52]; Keyvanshokooh et al., [53]; Kim and Lee [54], Amin and Zhang [55], Subramanian et al., [56]; Rosa et al., [57]) or a profit maximization (Alumur et al., [11]; Srivastava [23]; Lieckens and Vandaele [26]; Francas and Minner [58]; Sasikumar et al., [59]) objective. In our work, we consider varying revenues across different markets for the same item and thus model the problem with a profit maximization objective. Though most of the papers related to reverse logistics network design do not consider inventory related costs and environmental costs such as green-house emissions, Bazan et al., [20, 60, 61] strongly argue for the integration of environmental and societal factors in to reverse logistics modeling for the sustainability of businesses and organizations. In particular, Bazan et al., [20] carry out a comprehensive review of the mathematical inventory models for reverse logistics from an environmental perspective and conclude that even after 60 years of modeling development, the mathematical focus is mainly on EOQ related costs and recovery process costs.

In order to determine the flow of returned products at component and material level, it is essential to account for the bill of materials (BOM) of the product into the model. This aspect is all the more useful when there are multiple products and there exists component commonality among them. A few studies (see, for example, Dat et al., [2]; Alumur et al., [11]; Demirel et al., [12], Srivastava [23], Listes and Dekker [25], Chen et al., [62]) consider multi-product models. Except Dat, et al., [2], Alumur, et al., [11] and John et al., [70, 71], all the other studies analyze the flow of materials only at the product level rather than at the component level. In Dat, et al., [2] the term *disassembly tree* is used to consider the disassembled structure of the product. In Alumur, et al., [11] the reverse bill of material is employed to consider the product at the component and material level. A case study for washing machines and tumble dryers is considered in the context of reverse logistics network design. In John et al., [70, 71], though the authors consider BOM of the products, they study a single period model as opposed to a multi-period model.

In Table 1, we present a comprehensive picture of the features considered in our work vis-à-vis the earlier important contributions on network design. The table is not meant to be exhaustive. Yet, it gives a clear idea of the features and important design parameters that are considered in our work. Note that, in our view, carrying out a thoroughly exhaustive review of even a small slice of the supply chain literature is not entirely possible. To be exhaustive, in any sense, is difficult (and perhaps even unwarranted) when examining topics in reverse supply chains. In order to identify key research trends and gaps, we instead conduct an 'exemplary literature review' (see Rubin, et al [65]) in a systematic manner (see Khan et al [66] and Seuring and Gold [67]). We note here that an exemplary review is only illustrative of the extant literature. Thus, we present only representative references in an attempt to reacquaint the reader with key works in this area of research endeavor, while being careful not to overlook key references. In order to be systematic, we adopt a four-step process model (see Mayring [68] and Seuring and Gold [67]). We adopted a backward and forward snowballing approach, starting with seminal works, in order to search representative papers that explain trends and gaps in the field (Wohlin [69]). We followed the two-step-process proposed by Seuring and Gold [67] for category selection and then comprehensively (and independently) analyzed the literature that was thus collected so as to ensure transparency and replicability.

Table 1 Network design features

| **Article** | **Recovery options** | | | **Profit maximization** | **Multi-period** | **Product structure** | **Grading of product return** | **Exact solution methodology** |
|---|---|---|---|---|---|---|---|---|
| | **Remanufacturing** | **Recycling** | **Repairing** | | | | | |
| Alumur et al. [11] | Yes | No | No | Yes | Yes | Yes | No | Yes |
| Amin and Zhang [55] | Yes | No | No | No | No | No | Yes | Yes |
| Chen et al. [62] | Yes | Yes | No | Yes | No | No | Yes | No |
| Dat et al. [2] | No | Yes | Yes | No | No | Yes | No | Yes |
| Demirel et al. [12] | No | Yes | No | No | Yes | Yes | No | Yes |
| Diabat et al. [52] | No | No | No | No | No | No | No | No |
| Eskandarpour et al. [36] | No | Yes | Yes | No | No | No | Yes | No |
| Hatefi and Jolai [32] | Yes | No | No | No | No | No | Yes | Yes |
| Keyvanshokooh et al. [53]; | Yes | No | Yes | No | Yes | No | Yes | Yes |
| Kim and Lee [54] | No | No | No | No | Yes | No | No | No |
| Roghanian and Pazhoheshfar [37] | Yes | Yes | No | No | No | No | No | No |
| Soleimani et al. [40] | Yes | Yes | Yes | Yes | No | No | Yes | Yes |
| Suyabatmaz et al. [39] | No | No | No | No | No | No | Yes | Yes |
| Our work | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |

To summarize, although we see many papers in the area of reverse logistics network design, most of the studies do not consider some vital features that are important from a practical perspective. In spite of similarities between Alumur et al., [11] and our work, it is important to note that the modeling approach in both the cases is significantly different. Our work primarily focuses on the development of a unified network design that withstands variation in different input parameters such as product return quantity, unit transportation cost and unit processing cost.

Many features of practical relevance namely, multi-period scenario, consideration of bill of materials, simultaneous consideration of different recovery options, and a profit maximizing objective function have been addressed in our work. In that sense, our work fills a gap that is present in the literature. The problem that we look at is, therefore, worthy of study. We propose a few new models that plug the above gap. A further contribution of our work is that we then use these models to design the network for a refrigerator recovery supply chain.

## 3. Problem description and model formulation

As shown in Fig.1, the network structure consists of facilities such as product return zones, collection centers, remanufacturing centers and dismantling centers. The returned products from the customers are collected from the product return zones through collection centers. After proper inspection and grading at the collection centers, the products are classified into two categories based on their remaining useful life (RUL) as: (1) high RUL products and (2) low RUL products. High RUL products have the option of remanufacturing and can be sent for a new sale in secondary markets. Low RUL products are disassembled at dismantling centers and depending upon the nature of the components and their quality condition, these components are either repaired, recycled or disposed. The BOM of the product is incorporated into the model to analyze the flow through the network at component and material level. The disassembly of the product generates different items such as directly reusable components, faulty components, recyclable items and disposable items. Directly reusable components and repaired components are sold in the secondary markets, whereas recycled components are sold in the primary markets. Typically, disposable components are either non-recyclable or hazardous. Depending upon the nature of the component, they are either sent to a landfill or to an incinerator. The overall problem is to decide the location and the quantum of flow of products/components between pairs of facilities so as to maximize the revenues and minimize the total cost of setting up the facilities and other costs such as collection, processing, disposal, and transportation.

Now, we present the mixed integer linear programming model (MILP) developed for the problem. There are two important scope exclusions: a) Inventory related costs and b) Environment and social costs.

Inventory costs can be accounted for by introducing flow conservation constraints at all the facilities i.e., collection centers, remanufacturing centers, repairing centers, recycling centers, disposal sites, primary and secondary markets. Except the location of primary and secondary markets (retailers), the location decisions pertaining to the remaining facilities will be obtained via the network design. We first look at the need for including inventory costs at processing facilities (remanufacturing, repairing, and recycling centers). In the simplest scenario, a typical inventory flow conservation constraint is:

$$\mathrm{I_{t-1} - S_{t-1} + P_t - D_t = I_t - S_t} \tag{1}$$

Where,

$\mathrm{I_{t-1}}$ : Positive inventory at the end of period *'t-1'*

$\mathrm{S_{t-1}}$ : Negative inventory (shortage) at the end of period *'t-1'*

$\mathrm{P_t}$ : Production for period *'t'*

$\mathrm{D_t}$ : Demand for period *'t'*

From the above equation, it is clear that the demand for a period determines the inventory at the end of the corresponding period. The processing facilities are not demand centers by themselves. After processing, the used products are sent to primary and secondary markets depending on their condition. Hence, inventory costs cannot (and need not) be included at these facilities. Nevertheless, for argument sake, even if we assume some hypothetical demand numbers at each of these facilities, the corresponding equation will change as follows:

$$\mathrm{Y_{Rmfg}(I_{t-1} - S_{t-1} + P_t) - D_t = Y_{Rmfg}(I_t - S_t)} \tag{2}$$

Where, $\mathrm{Y_{Rmfg}}$ is a binary variable corresponding to the location decision of a facility.

Equation (2) ensures that inventory at a facility is accumulated only if the facility is "open". Otherwise, the binary variable will take a value of '0' making the constraint non-existent (or redundant). The above equation is non-linear (the binary variables pertaining to the location decisions have to be multiplied with inventory variables at every facility). Thus, the model cannot be solved using commercial optimization solvers such as LINGO or CPLEX.

Inventory costs could be included for the markets (retailers). As markets do not have location decisions associated with them, Equation (1) will be applicable without any non-linearities. This situation presents us with both an opportunity and a limitation. The opportunity is the provision for inclusion of inventory costs in the objective function which makes the problem more realistic and the limitation is that by merely adding the inventory costs into the objective function, the location decisions of other facilities do not get affected in anyway. In order to demonstrate this fact, we take the base case scenario explained in Section 4.1 as a test problem instance. The problem is solved with and without the inclusion of inventory costs at the markets. The results are tabulated in Table 2.

**Table 2 Network design decisions for the base case with and without inventory costs**

| Type of facility | With Inventory costs | Without inventory costs |
|---|---|---|
| Collection centre | 2, 3, 4, 5, 7 | 2, 3, 4, 5, 7 |
| Dismantling centre | 2, 3 | 2, 3 |
| Remanufacturing centre | 1, 2 | 1, 2 |
| Recycling centre | 2, 3 | 2, 3 |
| Repairing centre | 1, 3 | 1, 3 |
| Total profit | **412588.5** | **457443.0** |

The network design in both the cases turned out to be identical. The only difference observed is the reduction in the profit value when inventory costs are considered. We conclude that ignoring inventory carrying costs *may* result in some of bias in the overall profits of the supply chain. Based on the quantity returns and annual expenses at different facilities, our estimates suggest that it will be in the range of 15 – 20% for the "used refrigerator" case we have considered in this work.

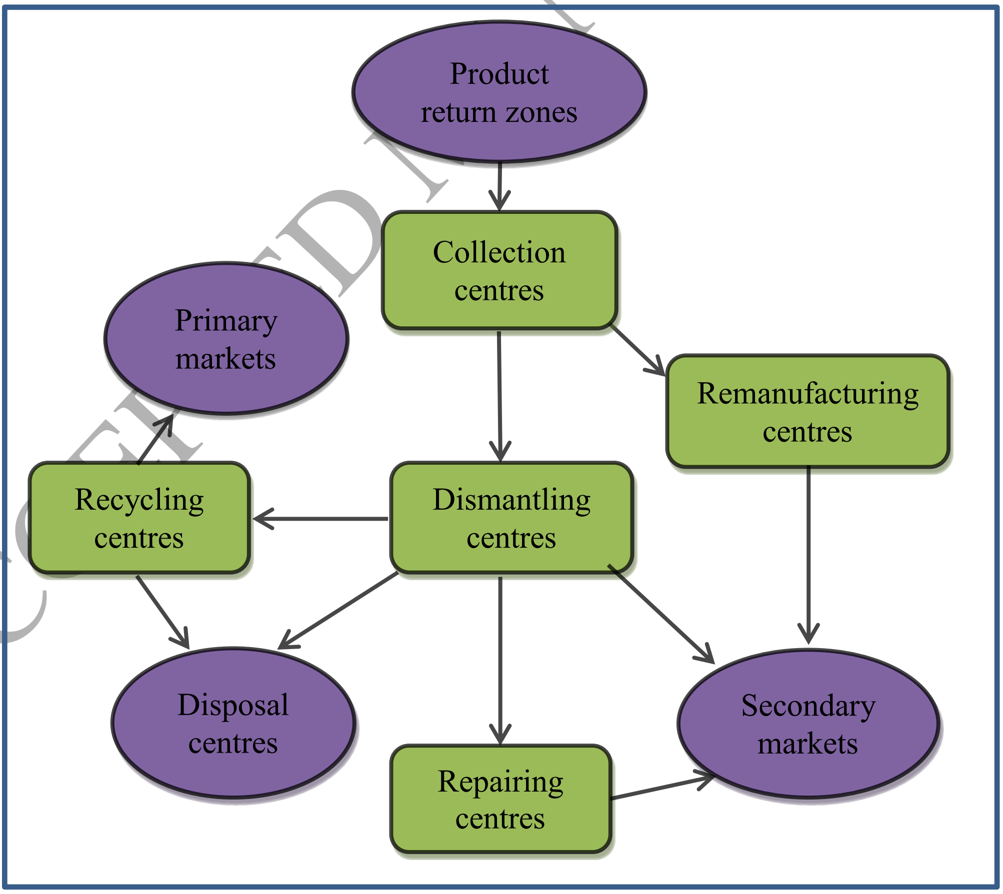

**Fig. 1 A reverse logistics network**

Along similar lines, accounting for environmental costs does not simply mean the introduction of a cost coefficient in the objective function. Practically, the final network design is arrived at by analyzing and assessing the strengths and weaknesses of alternative designs based on various factors. Particularly, environment and social costs form part of triple bottom line (TBL) framework that warrants an exhaustive analysis of environmental and social impact for every potential design of the network. We exclude such considerations from the purview of this work.

Though most of the input parameters such as quantity returns, transportation and processing costs do not remain constant over time, they are assumed to vary within a known range. It is considered that the unit transportation cost per unit distance of an item depends on the size of the item and the stage at which it is transported. The fixed cost for opening a particular type of facility depends not only on its capacity but also its location. The processing cost may also vary across different facilities of the same type, especially due to the nature and location of these facilities. These aspects are also considered in the proposed model. The major assumptions made in this study are as follows:

- There is only a single mode of transportation.
- There is adequate demand in the market for the processed items.
- The flow is only allowed to be transferred between two sequential echelons
- Product returns such as service returns, product recalls, warranty returns etc., are not considered in this study.

The formulation of the mixed integer linear programming model is presented as follows:

**Model formulation**

The different notations used in this study are as follows:

**Sets**

| | |
|---|---|
| $Z$ | Set of product return zones, indexed by $z$ |
| $C$ | Set of collection centers, indexed by $c$ |
| $D$ | Set of dismantling centers, indexed by $d$ |
| $L$ | Set of recycling centers, indexed by $l$ |
| $G$ | Set of repairing centers, indexed by $g$ |
| $R$ | Set of remanufacturing centers, indexed by $r$ |
| $V$ | Set of primary markets, indexed by $v$ |
| $S$ | Set of secondary markets, indexed by $s$ |
| $K$ | Set of disposal centers, indexed by $k$ |
| $P$ | Set of product return, indexed by $p$ |

| | |
|---|---|
| $A$ | Set of all stages in the network through which flow is allowed |
| $I$ | Set of all items in the network |
| $P^{RI}$ | Set of recyclable items |
| $P^{DI}$ | Set of disposable items |
| $P^{HI}$ | Set of hazardous/non-recyclable items |
| $P^{RM}$ | Set of recycled materials |
| $P^{DC}$ | Set of directly reusable components |
| $P^{FC}$ | Set of faulty components |
| $P^{RC}$ | Set of repaired components |
| $P^{RP}$ | Set of remanufactured products |
| $i, j$ | Index set for different types of items in the network, $(i, j) \in \{P, P^{RI}, P^{DI}, P^{HI}, P^{RM}, P^{DC}, P^{FC}, P^{RC}, P^{RP}\}$ |
| $m, n$ | Index set for facility locations in the network |

**Parameters**

| | |
|---|---|
| $PR_z$ | Number of products returned (PR) to product return zone $z$, |
| $CC$ | Unit collection cost (CC) of the product, |
| $PC_{ni}$ | Unit processing cost (PC) of product/component $i$, at facility $n$, where $n \in \{C, D, R, G, L\}$ and $i \in \{P, P^{RI}, P^{FC}\}$ |
| $U_i$ | Unit cost of disposal of material $i$, where $i \in \{P^{DI}, P^{HI}\}$ |
| $dist_{mn}$ | Distance between facilities $m$ and $n$, where $(m, n) \in A$ |
| $TC_{mni}$ | Unit transportation cost (TC) of item $i$ per unit distance, shipped from facility $m$ to $n$, where $i \in I$ and $(m, n) \in A$ |
| $FC_c, FC_d, FC_r, FC_g, FC_l$ | Fixed cost (FC) of opening and operating processing facilities, where $c \in C$, $d \in D$, $r \in R$, $g \in G$, $l \in L$ |
| $CAP_{ni}$ | Capacity (CAP) of facility $n$, for product/component $i$, where $n \in \{C, D, R, G, L\}$ and $i \in \{P, P^{RI}, P^{FC}\}$ |
| $REV_{ni}$ | Revenue (REV) obtained from market $n$ for item $i$, where $n \in \{V, S\}$ and $i \in \{P^{RM}, P^{DC}, P^{RC}, P^{RP}\}$ |
| $\propto$ | Percentage of returned products which belongs to higher RUL category |
| $NC_{ij}$ | Number of units of an item of type $j$ produced from product/component $i$ |
| $INR$ | Indian National Rupees |

**Decision variables**

$x_{mni}$ Quantity of item $i$ shipped from facility $m$ to facility $n$, where $(m, n) \in A$ and $i \in I$

$Y_c$ {0, 1} variable, $Y_c = 1$ if collection centre $c$ is open, else $Y_c = 0$, $\forall\, c \in C$

$Y_d$ {0, 1} variable, $Y_d = 1$ if dismantling center $d$ is open, else $Y_d = 0$, $\forall\, d \in D$

$Y_l$ {0, 1} variable, $Y_l = 1$ if recycling centre $l$ is open, else $Y_l = 0$, $\forall\, l \in L$

$Y_g$ {0, 1} variable, $Y_g = 1$ if repairing centre $f$ is open, else $Y_g = 0$, $\forall\, g \in G$

$Y_r$ {0, 1} variable, $Y_r = 1$ if remanufacturing centre $r$ is open, else $Y_r = 0$, $\forall\, r \in R$

**The Model**

**Maximise**

$$\begin{aligned}
&\left(\sum_{d\in D}\sum_{s\in S}\sum_{i\in P^{DC}} x_{dsi}\,REV_{si} + \sum_{g\in G}\sum_{s\in S}\sum_{i\in P^{RC}} x_{gsi}REV_{si} + \sum_{l\in L}\sum_{v\in V}\sum_{i\in P^{RM}} x_{lvi}\,REV_{vi}\right.\\
&\left.+\sum_{r\in R}\sum_{s\in S}\sum_{i\in P^{RP}} x_{rsi}REV_{si}\right) - \left(\sum_{z\in Z}\sum_{c\in C}\sum_{i\in P} x_{zci}(TC_{zci}dist_{zc} + PC_{ci} + CC)\right.\\
&+\sum_{c\in C}\sum_{r\in R}\sum_{i\in P} x_{cri}(TC_{cri}dist_{cr} + PC_{ri}) + \sum_{c\in C}\sum_{d\in D}\sum_{i\in P} x_{cdi}(TC_{cdi}dist_{cd} + PC_{di})\\
&+\sum_{r\in R}\sum_{s\in S}\sum_{i\in P^{RP}} x_{rsi}(TC_{rsi}dist_{rs}) + \sum_{d\in D}\sum_{g\in G}\sum_{i\in P^{FC}} x_{dgi}\big(TC_{dgi}dist_{dg} + PC_{gi}\big)\\
&+\sum_{d\in D}\sum_{s\in S}\sum_{i\in P^{DC}} x_{dsi}(TC_{dsi}dist_{ds}) + \sum_{d\in D}\sum_{l\in L}\sum_{i\in P^{RI}} x_{dli}(TC_{dli}dist_{dl} + PC_{li})\\
&+\sum_{d\in D}\sum_{k\in K}\sum_{i\in P^{DI}} x_{dki}(TC_{dki}dist_{dk} + U_i) + \sum_{g\in G}\sum_{s\in S}\sum_{i\in P^{RC}} x_{gsi}\big(TC_{gsi}dist_{gs}\big)\\
&+\sum_{l\in L}\sum_{v\in V}\sum_{i\in P^{RM}} x_{lvi}(TC_{lvi}dist_{lv}) + \sum_{l\in L}\sum_{k\in K}\sum_{i\in P^{HI}} x_{lki}(TC_{lki}dist_{lk} + U_i) + \sum_{c\in C} FC_cY_c + \sum_{r\in R} FC_rY_r\\
&\left.+\sum_{d\in D} FC_dY_d + \sum_{g\in G} FC_gY_g + \sum_{l\in L} FC_lY_l\right) \quad (3)
\end{aligned}$$

Subject to:

$$\sum_{c\in C} x_{zci} \le PR_z \qquad \forall\, i \in P, \forall\, z \in Z \qquad (returned\ products) \qquad (4)$$

$$\sum_{z\in Z} x_{zci} \times\!\propto\, \ge \sum_{r\in R} x_{cri} \qquad \forall\, i \in P, \forall\, c \in C \qquad (flow\ to\ remanuf.centre) \qquad (5)$$

$$\sum_{z\in Z} x_{zci} = \sum_{d\in D} x_{cdi} + \sum_{r\in R} x_{cri} \quad \forall\, i \in P, \forall\, c \in C \qquad (col.cen.outflow) \qquad (6)$$

$$\sum_{c\in C}\sum_{i\in P} x_{cri} \times NC_{ij} = \sum_{s\in S} x_{rsj} \quad \forall\, j\, \in P^{RP}, \forall\, r \in R \quad (remanuf.prod.) \tag{7}$$

$$\sum_{c\in C}\sum_{i\in P} x_{cdi} \times NC_{ij} = \sum_{s\in S} x_{dsj} \quad \forall\, j \in P^{DC}, \forall\, d \in D \;\; (dir.reusable\ parts) \tag{8}$$

$$\sum_{c\in C}\sum_{i\in P} x_{cdi} \times NC_{ij} = \sum_{g\in G} x_{dgj} \quad \forall\, j \in P^{FC}, \forall\, d \in D \quad (faulty\ parts) \tag{9}$$

$$\sum_{c\in C}\sum_{i\in P} x_{cdi} \times NC_{ij} = \sum_{l\in L} x_{dlj} \quad \forall\, j \in P^{RI}, \forall\, d \in D \qquad (recyclable\ parts) \tag{10}$$

$$\sum_{c\in C}\sum_{i\in P} x_{cdi} \times NC_{ij} = \sum_{k\in K} x_{dkj} \quad \forall\, j\, \in P^{DI}, \forall\, d \in D \quad (disposable\ items) \tag{11}$$

$$\sum_{d\in D}\sum_{i\in P^{FC}} x_{dgi} \times NC_{ij} = \sum_{s\in S} x_{gsj} \quad \forall\, j \in P^{RC}, \forall\, g \in G \quad (repaired\ parts) \tag{12}$$

$$\sum_{d\in D}\sum_{i\in P^{RI}} x_{dli} \times NC_{ij} = \sum_{v\in V} x_{lvj} \;\; \forall\, j \in P^{RM}, \forall\, l \in L \quad (recycled\ materials) \tag{13}$$

$$\sum_{d\in D}\sum_{i\in P^{RI}} x_{dli} \times NC_{ij} = \sum_{k\in K} x_{lkj} \;\; \forall\, j \in P^{HI}, \forall\, l \in L \qquad (nonrecy.materi.) \tag{14}$$

$$\sum_{z\in Z} x_{zci} \le CAP_{ci}\ \times Y_c \qquad \forall\, i \in P, \forall\, c \in C \qquad (collection\ centre) \tag{15}$$

$$\sum_{c\in C} x_{cri} \le CAP_{ri}\ \times Y_r \forall\ \mathrm{i} \in \mathrm{P}, \forall\, r \in R \qquad (remanufacturing\ centre) \tag{16}$$

$$\sum_{c\in C} x_{cdi} \le CAP_{di}\ \times Y_d \quad \forall\, i \in P, \forall\, d \in D \qquad (disassembly\ centre) \tag{17}$$

$$\sum_{d\in D} x_{dgi} \le CAP_{gi}\ \times Y_g \quad \forall\, i \in P^{FC}, \forall\, g \in G \quad (repairing\ centre) \tag{18}$$

$$\sum_{d\in D} x_{dli} \le CAP_{li}\ \times Y_l \qquad \forall\, i \in P^{RI}, \forall\, l \in L \quad (recycling\ centre) \tag{19}$$

$$Y_c, Y_r, Y_d, Y_l, Y_g \in \{0, 1\} \forall\, c \in C, \forall\, r \in R, \forall\, d \in D, \forall\, l \in L, \forall\, g \in G \tag{20}$$

$$x_{mni} = \begin{cases} \ge 0 & \forall (m,n) \in A, \forall\, i \in I \\ \ge 0 \text{ and integer} & \forall (m,n) \in A, \forall\, i \in I \text{ except} \forall\, i \in \{P^{DI}, P^{HI}, P^{RM}\} \end{cases} \tag{21}$$

The objective (3) maximizes the total profit of the supply chain. The resale of repaired components, directly reusable components, recycled materials and remanufactured products generates revenue in the supply chain. Different costs considered in the total cost function are transportation cost, processing cost at different facilities, disposal cost, collection cost and fixed opening and operating costs of facilities.

Constraints (4) to (14) represent the flow constraints. Constraint (4) indicates the restriction on the maximum flow from a product return zone to different collection centers depending on the availability of the returned product. Constraint (5) shows the restriction on the maximum flow to remanufacturing centers from a collection center based on the grade of product return. Constraint (6) implies that the total inflow to a collection center from all product return zones should be equal to the total outflow from it to remanufacturing centers and dismantling centers. Constraint (7) represents the conservation of flow of products at remanufacturing centers.

Constraints (8), (9), (10) and (11) represent the conservation of flow at dismantling centers for directly reusable components, faulty components, recyclable items and disposable/hazardous items respectively. Constraint (12) represents the conservation of flow of repairing centers. Constraints (13) and (14) represent the conservation of flow at recycling centers for recyclable materials and non-recyclable/hazardous materials respectively.

Constraints (15)-(19) are the capacity constraints of different facilities. Constraint (15) represents the capacity restriction of collection centers for the returned products. Constraint (16) represents the capacity restrictions of remanufacturing centers for the higher grade products. Constraint (17) implies that the total product flow into a dismantling center should be less than or equal to its capacity. The maximum allowable flow of each type of faulty component to different repairing centers is given in (18).

Constraint (19) implies that the total flow of each type of a recyclable item to a recycling center cannot exceed its capacity. Constraint (20) represents the binary nature of the decision variable for facility opening decisions. Constraint (21) represents the non-negativity and integer nature of flow between different stages of the supply chain. However, for material flow there is no integer restriction as it can be moved in fractional units.

## 4. Model validation and computational results

The mathematical model formulated in Section 3 is now validated with the design of a reverse supply chain which collects and processes used refrigerators. The company that provided us with the guidelines for data generation to validate the math model is one of the India’s largest 3PL service providers (based out of Bengaluru) specializing in reverse logistics. The company has been contracted by a reputed OEM to collect used refrigerators from the five southern Indian states of Tamil Nadu, Karnataka, Kerala, Maharashtra, and Andhra Pradesh. Together, these five states represent 20% of the Indian population roughly translating to 200 million.  Refrigerators have a strong demand with an average lifespan of about 8 to 10 years. Considering the size of the population and lifespan of the product, the product return rate is uniformly distributed in the range 600 to 1000 for every return zone. The different parameters of the model were obtained by consulting the managers of the organization (Please refer to Appendix A). Our objective is to demonstrate the application of the mathematical model for the design of a reverse supply chain which grades the returned products based on remaining useful life (RUL). We also study the sensitivity of the design decisions with respect to variations of different input parameter values.

Today, used refrigerators are being disassembled and disposed-off in a manner that poses serious risks, health hazards and environmental contamination risks. Most of the existing processing facilities are general purpose workshops that handle a variety of items manned by semi-skilled workers. In view of this, we are unable to provide any comparison between the efficacies of the proposed network with that of existing setup. Indeed, any solutions that we provide through our modelling approach would be a necessary and substantial improvement to current practice.

All the problem instances were solved using LINGO optimization solver on a computer with Intel Core 2 Duo processor of 2.10 GHz speed and 2 GB RAM. The LINGO solver does a fair bit of pre-processing and adds valid inequalities and then uses branch-and-bound to find optimal solutions.

### *4.1 Data description*

The network for collecting used refrigerators (Figure 2) consists of five product return zones, seven potential locations of collection centers, four potential locations of dismantling centers, three potential locations each of remanufacturing centers, recycling centers and repairing centers, one disposal center, two primary markets and two secondary markets. The collected products are graded at collection centers and classified into two categories. The compressor of the refrigerator is considered as the heart of the refrigerator and if it is not in working condition, the refrigerator is grouped into the category of low RUL products. The high RUL refrigerators can be remanufactured at remanufacturing centers. The different items in level 1 of the product structure diagram of a refrigerator are cooling coil, compressor, condenser, refrigerant, compressor oil and the main body of the refrigerator. The processing of different parts of the refrigerator is considered as follows:

- Polyurethane foam: The presence of CFC (chlorofluorocarbon) gases in PU foam that aid in the formation of ozone holes and global warming makes recycling of the product extremely complicated. Typically, there are three ways of recycling PU waste: Mechanical, Chemical, and Thermal. In mechanical recycling, processes such as adhesive pressing, regrinding, injection and compression moulding are employed to make carpet underlay, sports mats, automotive parts (door panels and dashboard panels) and cushioning products with recycled foam. In chemical recycling, processes such as Glycolysis, Hydrolysis, Pyrolysis and

Hydrogenation are used to recover polyols and diaminotoulenes (DATs) for manufacturing of dyes and polyesters used in textile industries. The residue is disposed in a landfill. Thermal recycling implies the usage of PU foam as a raw material for waste-to-energy facilities to generate power. But the incineration of PU foam has its own limitations. Unless incinerated under controlled conditions, the CFCs will easily find their way into the atmosphere. In this work, it is considered that the PU foam obtained from the used refrigerators is chemically treated before sending to a landfill.

- Refrigerant oil: Oil contained in most refrigerated systems comes in continual contact with halogenated hydrocarbon refrigerants and get contaminated. It is environmentally hazardous to send it to a landfill without recovering the refrigerants. In order to recover the refrigerant from the contaminated oil, distillation process is carried out by heating the oil to approximately 120C for about 8 hours in an enclosed container. After condensation, the refrigerant gases volatized from the heated oil is collected and the residual oil is sent to solid waste energy recovery plants. The refrigerant gases can be reused.
- Plastic materials: The plastic parts that are used in a refrigerator are mostly made of plastics such as ABS (Acrylonitrile Butadiene Styrene), Polypropylene and polystyrene which are recyclable. Parts such as drawers, shelves and vegetable cases can directly be chipped and melted down into pellets. The inner cabinet including inner liners are also made of plastic that is recyclable. The cabinet is fed to a shredding machine followed by four stages of separation - pneumatic, magnetic, eddy current and specific gravity – to recover recyclable plastic.
- The ferrous materials from condenser and body parts are directly recycled.
- The refrigerant and the cooling coil are reused.
- The faulty compressor is repaired and sold in the secondary market.

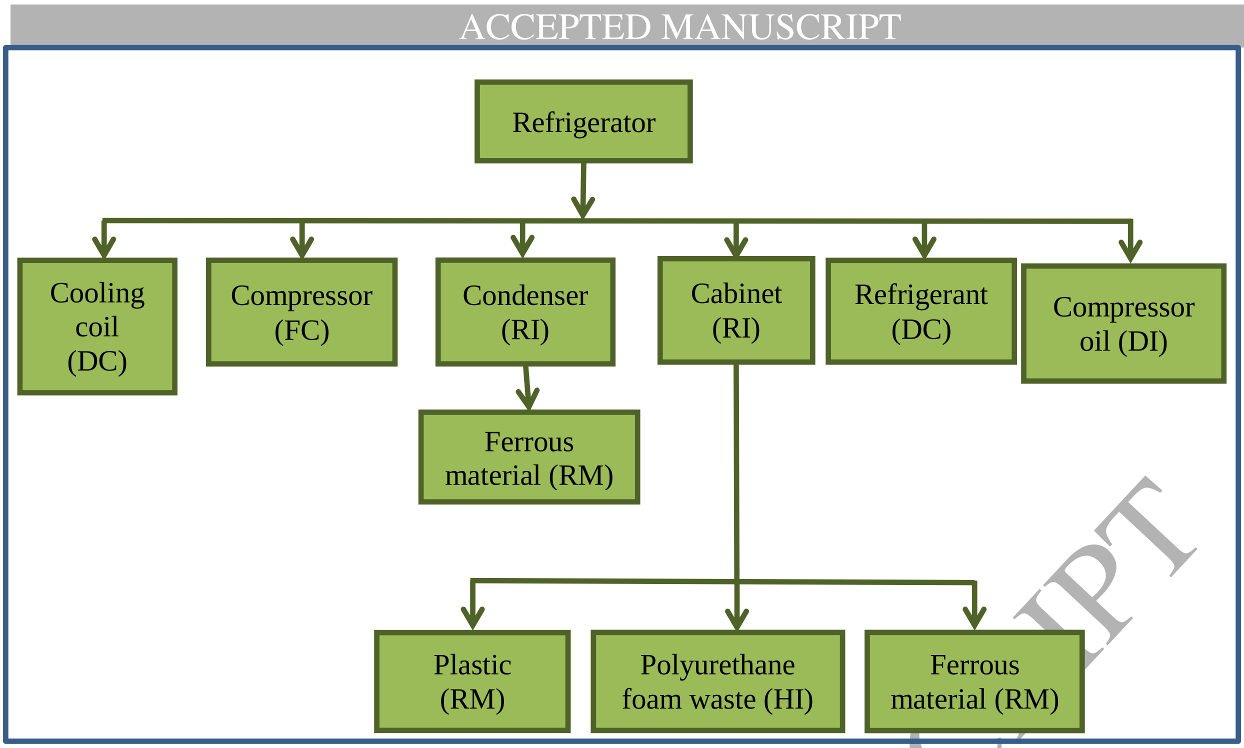

**Fig. 2 Product structure of a refrigerator**

The problem is to determine the optimum number and location of collection, dismantling, repairing, recycling and remanufacturing centers so that the total profit is maximized. The distribution channels of flow between different stages of the supply chain along with the quantities of flow are also to be determined. Unit collection cost for the used refrigerator is INR 900 and it is considered that on an average 30% of the returned products fall in the category of high RUL products.

The locations of different facilities are generated from a uniform distribution between 0 and 100 distance units on x and y coordinates and the distance between facilities is calculated by Euclidean method as considered in several research studies in the literature (see Jayaraman et al., [41], Min et al., [55]). The base case, used for computational experiments, represents the most likely real-life scenario in terms of product return quantities, unit transportation and processing costs. The pertinent data for the base case is presented in the Tables A5 – A10 in Appendix A. As shown in Table 3, the 13 different scenarios represent possible instances of variations in the values of different input parameters such as product return quantity, unit transportation cost and unit processing cost. Variations of 5%, 10% and 20% in input parameters have been arrived at based on the projections made by the company's sales and forecasting team. Also, over the next 5 years, the company expects relatively higher variation in product return quantities when compared to the costs and hence the difference in numbers.

It is noteworthy that though the 13 cases considered in this work may not exhaustively represent all possible future real-life scenarios, we chose to work on only these cases. This is because, in contrast to developed economies, the business of e-waste processing in developing countries such as India is still at nascent stages. Entrepreneurs in this field are cautious about making large investments in recycling facilities owing to lack of clarity in government policies with respect to e-waste processing and disposal. In most cases, “wait and watch’ policy is adopted before making big ticket investments. In this context, the company that we are working with has a strong sales and forecasting team that has come up with scientific market projections for the next 5 years regarding product return volumes, transportation and processing costs. It is based on these projections; the initial investments have been made. Even if some of the input parameters like product returns vary (increase) more than expected, the invested facilities have capacity constraints (in terms of skilled manpower, machines and physical size) and can only handle variations to the extent forecasted by the sales team. As the company is not willing to augment capacity for the next 5 years, it cannot process anything over and above these numbers and most likely it will result in lost sales. Precisely, the mathematical model is expected to generate a unified network design that can withstand the variation in input parameters for the next 5 years.

**Table 3 Variation of input parameters**

| Case | Product return | Unit transportation cost | Unit processing cost |
|---|---|---|---|
| 1 | Base case | Base case | Base case |
| 2 | 10 % decrease w.r.t. base case | Same as base case | Same as base case |
| 3 | 20 % decrease w.r.t. base case | Same as base case | Same as base case |
| 4 | 10 % increase w.r.t. base case | Same as base case | Same as base case |
| 5 | 20 % increase w.r.t. base case | Same as base case | Same as base case |
| 6 | Same as base case | 5 % decrease w.r.t. base case | Same as base case |
| 7 | Same as base case | 10 % decrease w.r.t. base case | Same as base case |
| 8 | Same as base case | 5 % increase w.r.t. base case | Same as base case |
| 9 | Same as base case | 10 % increase w.r.t. base case | Same as base case |
| 10 | Same as base case | Same as base case | 5% decrease w.r.t. base case |
| 11 | Same as base case | Same as base case | 10% decrease w.r.t. base case |
| 12 | Same as base case | Same as base case | 5% increase w.r.t. base case |
| 13 | Same as base case | Same as base case | 10% increase w.r.t. base case |

### *4.2 Results and analyses*

Case 1 is considered as the base case. The optimum design decisions and performance measure values obtained for the base case are shown in Tables 4 and 5 respectively.

**Table 4 Facility opening decisions for the base case**

| Type of facility | Centres to be opened |
|---|---|
| Collection centre | 2, 3, 4, 5, 7 |
| Dismantling centre | 2, 3 |
| Remanufacturing centre | 1, 2 |
| Recycling centre | 2, 3 |
| Repairing centre | 1, 3 |

**Table 5 Performance measure values for the base case**

| Performance criterion (all monetary terms are in INR) | Base case |
|---|---|
| Total profit | 457443.0 |
| Total revenue | 9351830.0 |
| Total cost | 8894387.0 |
| Total collection cost | 3465000.0 |
| Total transportation cost | 1986347.0 |
| Total fixed facility cost | 677000.0 |
| Total disposal cost | 134750.0 |
| Total processing cost | 2631290.0 |
| Number of used products available for collection | 3850 |
| Number of used products collected | 3850 |

The distribution channels between different facilities and the quantities of flow of refrigerators, all its component parts and materials through these channels are also determined. The resulting network is shown in Figure 3.

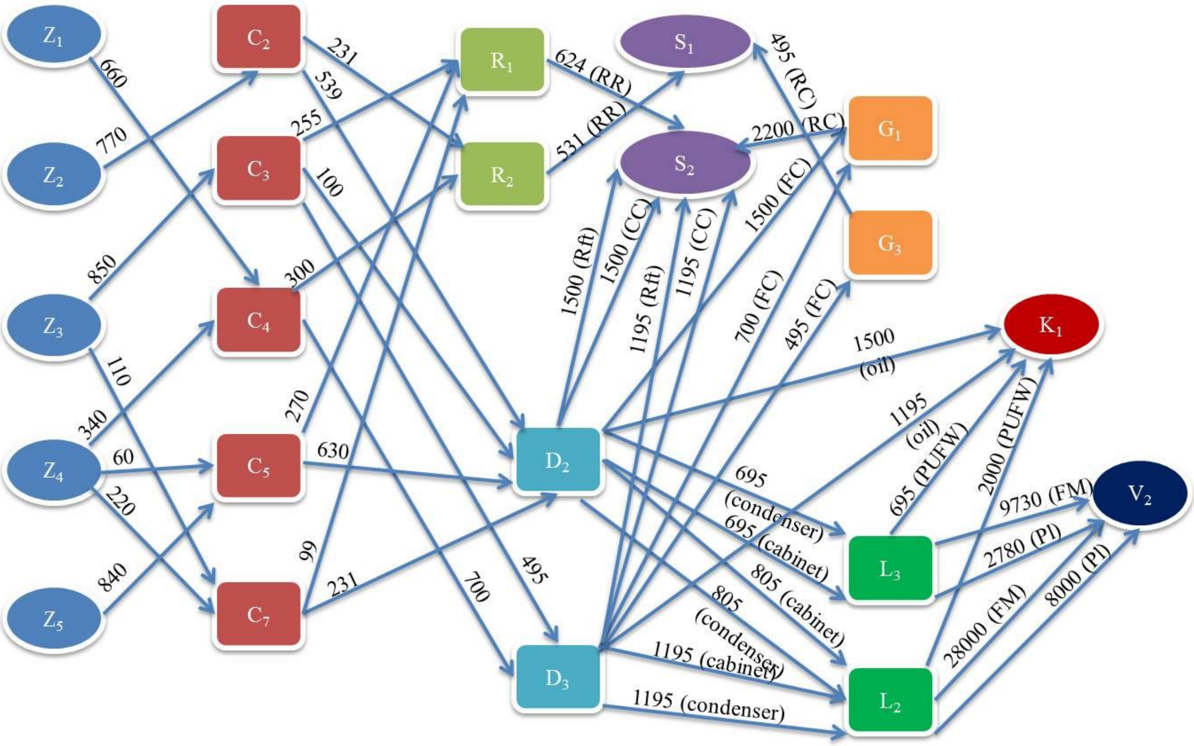

**Fig. 3 Network structure for the base case**

All other cases are also solved and the results are analyzed to study the effects of changes in product return rate, unit transportation cost and unit processing cost on network design decisions and performance measure values.

The analyses of the results obtained are presented in the following sub-sections.

### 4.2.1 *Effect of variation of product return rate*

In order to analyze the effect of variation of product return rate on network design decisions, four different levels of product return are considered in addition to the base case as shown in Table 3.

The comparison of design decisions and performance measure values for different cases of product return are provided in Table 6.

**Table 6 Comparison of facility opening decisions of the model for different settings of product return**

| Type of facility | Centres to be opened | | | | |
|---|---|---|---|---|---|
| | Base case | Case 2 | Case 3 | Case 4 | Case 5 |
| Collection centre | 2, 3, 4, 5, 7 | 2, 3, 4, 5 | 2, 3, 4, 5 | 1, 3, 4, 5, 7 | 1, 2, 3, 4, 5, 7 |
| Dismantling centre | 2, 3 | 2, 4 | 2, 4 | 2,3 | 2, 3 |
| Remanufacturing centre | 1, 2 | 3 | 3 | 2,3 | 2, 3 |
| Recycling centre | 2, 3 | 2 | 2 | 2,3 | 2, 3 |
| Repairing centre | 1, 3 | 1 | 1 | 1,3 | 1, 3 |

From Table 6, it is observed that there are some significant variations in the design decisions when the product return quantity varies within the range provided. The decisions regarding collection centers are considerably changed for other cases as compared to the base case. In the base case, the optimum decision involves opening collection centers 2, 3, 4, 5 and 7.

In Cases 2 and 3, with decrease in product return quantity the number of collection centers also decreases. It is also observed that the decisions regarding other types of facilities are also considerably different for the product return variation. In actual practice, the frequent changes in the network design decisions cannot be easily incorporated into the network due to its strategic nature.

However, the variations in the available product return quantity at product return zones are inevitable over different time periods and the analysis shows the importance of incorporating these variations into the mathematical model for obtaining a unified design.

The values of total profit, total revenue, total cost and different cost components are also obtained for these cases as shown in Table 7.

**Table 7 Comparison of performance measure values for different settings of product return**

| Performance criterion (all monetary terms are in INR) | Base case | Case 2 | Case 3 | Case 4 | Case 5 |
|---|---|---|---|---|---|
| Total profit | 457443.0 | 432978.0 | 412173.5 | 509822.4 | 563480.4 |
| Total revenue | 9351830.0 | 6970150.0 | 6970150.0 | $1.027898\times10^7$ | $1.109242\times10^7$ |
| Total cost | 8894387.0 | 6537172.0 | 6557976.0 | 9769154.0 | $1.052894\times10^7$ |
| Total collection cost | 3465000.0 | 2571300.0 | 2571300.0 | 3810600.0 | 4113000.0 |
| Total transportation cost | 1986347.0 | 1420141.0 | 1442502.0 | 2201684.0 | 2374264.0 |
| Total fixed facility cost | 677000.0 | 457000.0 | 457000.0 | 687000.0 | 726000.0 |
| Total disposal cost | 134750.0 | 100000.0 | 100000.0 | 148200.0 | 159950.0 |
| Total processing cost | 2631290.0 | 1988731.0 | 1987175.0 | 2921670.0 | 3155722.0 |
| Number of used products available for collection | 3850 | 3465 | 3080 | 4235 | 4620 |
| Number of used products collected | 3850 | 2857 | 2857 | 4235 | 4570 |

### *4.2.2 Effect of variation of unit transportation cost per unit distance*

The unit transportation cost per unit distance is set at five different levels and the solutions obtained for these cases are provided in Tables 8 and 9.

**Table 8 Comparison of facility opening decisions of the model for different settings of unit transportation cost per unit distance**

| Type of facility | Centres to be opened | | | | |
|---|---|---|---|---|---|
| | Base case | Case 6 | Case 7 | Case 8 | Case 9 |
| Collection centre | 2, 3, 4, 5, 7 | 2, 3, 4, 5, 7 | 2, 3, 4, 5, 7 | 2, 3, 5, 7 | 2, 3, 5, 7 |
| Dismantling centre | 2, 3 | 2, 3 | 2, 3 | 2, 4 | 2, 4 |
| Remanufacturing centre | 1, 2 | 1, 2 | 1, 2 | 3 | 3 |
| Recycling centre | 2, 3 | 2, 3 | 2, 3 | 2 | 2 |
| Repairing centre | 1, 3 | 1, 3 | 1, 3 | 1 | 1 |

**Table 9 Comparison of performance measure values for different settings of unit transportation cost**

| Performance criterion (all monetary terms are in INR) | Base case | Case 6 | Case 7 | Case 8 | Case 9 |
|---|---|---|---|---|---|
| Total profit | 457443.0 | 556760.3 | 656107.6 | 376889.7 | 306493.5 |
| Total revenue | 9351830.0 | 9351830.0 | 9353130.0 | 6970150.0 | 6970150.0 |
| Total cost | 8894387.0 | 8795070.0 | 8697022.0 | 6593260.0 | 6663656.0 |
| Total collection cost | 3465000.0 | 3465000.0 | 3465000.0 | 2571300.0 | 2571300.0 |
| Total transportation cost | 1986347.0 | 1887030.0 | 1789502.0 | 1478321.0 | 1548718.0 |
| Total fixed facility cost | 677000.0 | 677000.0 | 677000.0 | 453000.0 | 453000.0 |
| Total disposal cost | 134750.0 | 134750.0 | 134750.0 | 100000.0 | 100000.0 |
| Total processing cost | 2631290.0 | 2631290.0 | 2630770.0 | 1990639.0 | 1990639.0 |
| Number of used products available for collection | 3850 | 3850 | 3850 | 3850 | 3850 |
| Number of used products collected | 3850 | 3850 | 3850 | 2857 | 2857 |

It is interesting to note that the network configuration remains same with decrease in transportation costs (Cases 6 and 7) but changes with increase in transportation costs (Cases 8 and 9).

Our reasoning is that, owing to higher transportation costs, it may be expensive to collect all the available used products and process them. Hence the model suggests collecting lesser number of products. As the number of collected products itself is less, opening as many facilities as the base case may not be economically viable. So, the final network configuration is considerably different for Cases 8 and 9.

Within Cases 6 and 7, even though the quantities of products collected are the same, the variation in unit transportation cost per unit distance changes the product flow between different stages as observed from the variations in the total processing cost and total revenue.

### 4.2.3 *Effect of variation of unit processing cost*

The optimum design decisions of different facilities for the unit processing cost variation are provided in Table 10.

**Table 10 Comparison of facility opening decisions for different settings of unit processing cost**

| Type of facility | Centres to be opened | | | | |
|---|---|---|---|---|---|
| | Base case | Case 10 | Case 11 | Case 12 | Case 13 |
| Collection centre | 2, 3, 4, 5, 7 | 2, 3, 4, 5, 7 | 2, 3, 4, 5, 7 | 2, 3, 5, 7 | 2, 3, 5, 7 |
| Dismantling centre | 2, 3 | 2, 3 | 2, 3 | 2, 4 | 2, 4 |
| Remanufacturing centre | 1, 2 | 1, 2 | 1, 2 | 3 | 3 |
| Recycling centre | 2, 3 | 2, 3 | 2, 3 | 2 | 2 |
| Repairing centre | 1, 3 | 1, 3 | 1, 3 | 1 | 1 |

It is observed that the variation of unit processing cost has the same effect as that of the unit transportation cost on network configuration. With decrease in processing costs (Cases 10 and 11), there is no change in the network configuration. But with increase in processing costs (Cases 12 and 13), the model suggests processing lesser quantities of product returns thereby obviating the need to open as many facilities as that of the base case. The total profit, total revenue, total cost and different cost component values in each of these cases are tabulated in Table 11.

**Table 11 Comparison of performance measure values for different settings of unit processing cost**

| Performance criterion (all monetary terms are in INR) | Base case | Case 10 | Case 11 | Case 12 | Case 13 |
|---|---|---|---|---|---|
| Total profit | 457443.0 | 589007.5 | 720572.0 | 347754.1 | 248222.1 |
| Total revenue | 9351830.0 | 9351830.0 | 9351830.0 | 6970150.0 | 6970150.0 |
| Total cost | 8894387.0 | 8762822.0 | 8631258.0 | 6622396.0 | 6721928.0 |
| Total collection cost | 3465000.0 | 3465000.0 | 3465000.0 | 2571300.0 | 2571300.0 |
| Total transportation cost | 1986347.0 | 1986347.0 | 1986347.0 | 1407925.0 | 1407925.0 |
| Total fixed facility cost | 677000.0 | 677000.0 | 677000.0 | 453000.0 | 453000.0 |
| Total disposal cost | 134750.0 | 134750.0 | 134750.0 | 100000.0 | 100000.0 |
| Total processing cost | 2631290.0 | 2499726.0 | 2368161.0 | 2090171.0 | 2189703.0 |
| Number of used products available for collection | 3850 | 3850 | 3850 | 3850 | 3850 |
| Number of used products collected | 3850 | 3850 | 3850 | 2857 | 2857 |

### 4.2.4 *Summary of the findings from the sensitivity analyses*

The sensitivity analyses conducted show that the design decisions change considerably even for small variations in different input parameter values. In actual practice, the input parameter values change over different periods due to a variety of reasons. Nevertheless, the optimum network design cannot vary over different periods. In reality, the cost of closing and reopening a facility is significantly high. For example, [63, 64] consider the closing penalties to be the same as the set-up costs of the corresponding facilities, while reopening penalties are twice that of the closing penalties.

Thus, it is not conceivable that facilities may be opened and closed at will, over time, as our initial model may seem to suggest. The subsequent sensitivity analyses performed in this study shows the importance of incorporating input parameter variations over time into the mathematical model itself so that these changes may be incorporated while designing the network. The objective is to derive a unified design which maximizes the total profit of the supply chain over the entire planning horizon.

## 5. Incorporating input parameter variations

The mathematical model formulated in Section 3 is extended in this section to incorporate the variations of different input parameter values over time.

### *5.1 Mathematical modelling*

The additional notations used in this model are as follows:

| | |
|---|---|
| $T$ | Set of time periods in the planning horizon, indexed by $t$ |
| $PR_{tz}$ | Number of products returned to product return zone $z$ in time period $t$, where $z \in Z$ and $t \in T$ |
| $TC_{tmni}$ | Unit transportation cost (TC) of item $i$ per unit distance, shipped from facility $m$ to $n$, in time period $t$, where $i \in I$, $(m, n) \in A$, and $t \in T$ |
| $PC_{tni}$ | Unit processing cost of product/component $i$, at facility $n$, where $i \in \{P, P^{RI}, P^{FC}\}$, $n \in \{C, D, R, G, L\}$ and $t \in T$ |
| $Q$ | Number of time periods in the planning horizon |
| $x_{tmni}$ | Quantity of item $i$ shipped from facility $m$ to facility $n$ in period $t$, where $i \in I$, $(m, n) \in A$ and $t \in T$ |

The mathematical model is formulated as follows:

**Maximise**

$$\left(\sum_{t\in T}\sum_{d\in D}\sum_{s\in S}\sum_{i\in P^{DC}} x_{tdsi}\,REV_{si} + \sum_{t\in T}\sum_{g\in G}\sum_{s\in S}\sum_{i\in P^{RC}} x_{tgsi}REV_{si} + \sum_{t\in T}\sum_{l\in L}\sum_{v\in V}\sum_{i\in P^{RM}} x_{tlvi}\,REV_{vi} + \sum_{t\in T}\sum_{r\in R}\sum_{s\in S}\sum_{i\in P^{RP}} x_{trsi}REV_{si}\right) - \left(\sum_{t\in T}\sum_{z\in Z}\sum_{c\in C}\sum_{i\in P} x_{tzci}(TC_{tzci}dist_{zc} + PC_{tci} + CC) + \sum_{t\in T}\sum_{c\in C}\sum_{r\in R}\sum_{i\in P} x_{tcri}(TC_{tcri}dist_{cr} + PC_{tri}) + \sum_{t\in T}\sum_{c\in C}\sum_{d\in D}\sum_{i\in P} x_{tcdi}(TC_{tcdi}dist_{cd} + PC_{tdi}) + \sum_{t\in T}\sum_{r\in R}\sum_{s\in S}\sum_{i\in P^{RP}} x_{trsi}(TC_{trsi}dist_{rs}) + \sum_{t\in T}\sum_{d\in D}\sum_{g\in G}\sum_{i\in P^{FC}} x_{tdgi}(TC_{tdgi}dist_{dg} + PC_{tgi}) + \sum_{t\in T}\sum_{d\in D}\sum_{s\in S}\sum_{i\in P^{DC}} x_{tdsi}(TC_{tdsi}dist_{ds}) + \sum_{t\in T}\sum_{d\in D}\sum_{l\in L}\sum_{i\in P^{RI}} x_{tdli}(TC_{tdli}dist_{dl} + PC_{tli}) + \sum_{t\in T}\sum_{d\in D}\sum_{k\in K}\sum_{i\in P^{DI}} x_{tdki}(TC_{tdki}dist_{dk} + U_i) + \sum_{t\in T}\sum_{g\in G}\sum_{s\in S}\sum_{i\in P^{RC}} x_{tgsi}(TC_{tgsi}dist_{gs}) + \sum_{t\in T}\sum_{l\in L}\sum_{v\in V}\sum_{i\in P^{RM}} x_{tlvi}(TC_{tlvi}dist_{lv}) + \sum_{t\in T}\sum_{l\in L}\sum_{k\in K}\sum_{i\in P^{HI}} x_{tlki}(TC_{tlki}dist_{lk} + U_i) + \sum_{c\in C} FC_cY_cQ + \sum_{r\in R} FC_rY_rQ + \sum_{d\in D} FC_dY_d\,Q + \sum_{g\in G} FC_gY_gQ + \sum_{l\in L} FC_lY_lQ\right) \quad (22)$$

Subject to the following constraints:

$$\sum_{c\in C} x_{tzci} \le PR_{tz} \qquad \forall\, i \in P, \forall\, z \in Z, \forall\, t \in T \qquad (returned\ products) \qquad (23)$$

$$\sum_{z\in z} x_{tzci} \times \propto\, \ge \sum_{r\in R} x_{tcri} \quad \forall\, i\ \in P, \forall\, c \in C, \forall\, t \in T \qquad (flow\ to\ remanu.cen.) \qquad (24)$$

$$\sum_{z\in z} x_{tzci} = \sum_{r\in R} x_{tcri} + \sum_{d\in D} x_{tcdi} \quad \forall\, i \in P, \forall\, c \in C, \forall\, t \in T \qquad (col.cen.flow) \qquad (25)$$

$$\sum_{c\in C}\sum_{i\in P} x_{tcri} \times NC_{ij} = \sum_{s\in S} x_{trsj} \quad \forall\, j \in P^{RP}, \forall\, r \in R, \forall\, t \in T \qquad (reman.\ \ prod.) \qquad (26)$$

$$\sum_{c\in C}\sum_{i\in P} x_{tcdi} \times NC_{ij} = \sum_{s\in S} x_{tdsj} \quad \forall\, j \in P^{DC}, \forall\, d \in D, \forall\, t \in T \qquad (di.reu.parts) \qquad (27)$$

$$\sum_{c\in C}\sum_{i\in P} x_{tcdi} \times NC_{ij} = \sum_{g\in G} x_{tdgj} \quad \forall\, j \in P^{FC}, \forall\, d \in D, \forall\, t \in T \qquad (faulty\ parts) \qquad (28)$$

$$\sum_{c\in C}\sum_{i\in P} x_{tcdi} \times NC_{ij} = \sum_{l\in L} x_{tdlj} \quad \forall\, j \in P^{RI}, \forall\, d \in D, \forall\, t \in T \qquad (recyc.parts) \qquad (29)$$

$$\sum_{c\in C}\sum_{i\in P} x_{tcdi} \times NC_{ij} = \sum_{k\in K} x_{tdkj} \quad \forall\, j\ \in P^{DI}, \forall\, d \in D, \forall\, t \in T \qquad (disp.items) \qquad (30)$$

$$\sum_{d\in D}\sum_{i\in P^{FC}} x_{tdgi} \times NC_{ij} = \sum_{s\in S} x_{tgsj} \quad \forall\, j \in P^{RC}, \forall\, g \in G, \forall\, t \in T \qquad (rep.parts) \qquad (31)$$

$$\sum_{d\in D}\sum_{i\in P^{RI}} x_{tdli}\times NC_{ij}=\sum_{v\in V} x_{tlvj}\quad \forall\, j\in P^{RM},\forall\, l\in L,\forall\, t\in T \qquad (recyc.mat.) \qquad (32)$$

$$\sum_{d\in D}\sum_{i\in P^{RI}} x_{tdli}\times NC_{ij}=\sum_{k\in K} x_{tlkj}\quad \forall\, j\in P^{HI},\forall\, l\in L,\forall\, t\in T \qquad (nonrecyc.) \qquad (33)$$

$$\sum_{z\in Z} x_{tzci}\le CAP_{ci}\times Y_c \qquad \forall\, i\in P,\forall\, c\in C,\forall\, t\in T \qquad (collection\ centre) \qquad (34)$$

$$\sum_{c\in C} x_{tcri}\le CAP_{ri}\times Y_r \qquad \forall\, i\in P,\forall\, r\in R,\forall\, t\in T \qquad (remanufact.centre) \qquad (35)$$

$$\sum_{c\in C} x_{tcdi}\le CAP_{di}\times Y_d \qquad \forall\, i\in P,\forall\, d\in D,\forall\, t\in T \qquad (disassembly\ centre) \qquad (36)$$

$$\sum_{d\in D} x_{tdgi}\le CAP_{gi}\times Y_g \qquad \forall\, i\in P^{FC},\forall\, g\in G,\forall\, t\in T \qquad (repairing\ centre) \qquad (37)$$

$$\sum_{d\in D} x_{tdli}\le CAP_{li}\times Y_l \qquad \forall\, i\in P^{RI},\forall\, l\in L,\forall\, t\in T \qquad (recycling\ centre) \qquad (38)$$

$$x_{tmni}=\begin{cases}\ge 0 & \forall\,(m,n)\in A,\forall\, i\in I,\forall\, t\in T\\ \ge 0\ and\ integer & \forall\,(m,n)\in A,\forall\, i\in I\ except\ \forall\, i\in\{P^{DI},P^{HI},P^{RM}\},\forall\, t\in T\end{cases} \qquad (39)$$

The objective function (22) maximizes the total profit of the supply chain over the entire planning horizon. Constraint (23) restricts the maximum flow of products from a product return zone to all collection centers in each period to the product availability at that product return zone in that period.

Constraint (24) shows the maximum allowable product flow from a collection center to different remanufacturing centers in each time period, based on the grade of product return. Constraints (25) to (33) represent the conservation of flow constraints of different items at different facilities in each of the period. Capacity limitations of different facilities for the flow of different items are given in constraints (34) to (38). Constraint (39) represents the non-negativity and integer nature of the flow variable in different periods. However, material flows do not have any integer restriction (as already stated in the previous section).

### *5.2 Model application and computational results*

The proposed model is applied to the network design problem of the refrigerator recovery supply chain described in the previous section. We consider a planning horizon with 5 time periods. The input parameters considered for each of the time periods is tabulated in Table 12.

**Table 12 Input parameters for the entire planning horizon**

| Period | Product return* | Unit transportation cost* | Unit processing cost* |
|---|---|---|---|
| **1** | Base case | Base case | Base case |
| **2** | 10 % decrease | 10 % decrease | 5 % increase |
| **3** | 10 % increase | 5 % increase | 20 % decrease |
| **4** | 10 % increase | 5 % decrease | 10 % increase |
| **5** | 20 % decrease | 10 % increase | 10 % decrease |

The data in period 1 is considered the same as that provided in the base case. For all other periods, the input parameters are varied within a range of ±20%. The unified network configuration indicating the number and location of different facilities to be established is given in Table 13. The values of different performance measures across different periods are reported in Tables 14 and 15. Though the quantity of flow of different items across different stages of the supply chain in each of the period are also obtained, for the sake of brevity of results, they are not reported in this paper.

**Table 13 Unified design of the network for the entire planning horizon**

| Type of facility | Centres to be opened |
|---|---|
| Collection centre | 2, 3, 4, 5 |
| Dismantling centre | 2, 4 |
| Remanufacturing centre | 3 |
| Recycling centre | 2 |
| Repairing centre | 1 |

**Table 14 Performance measure values for the entire planning horizon**

| Performance criterion (all monetary terms are in INR) | Value |
|---|---|
| Total profit | **2223209** |
| Total revenue | **3.485075×107** |
| Total cost | **3.262754×107** |
| Total collection cost | **1.285650×107** |
| Total transportation cost | **7040456** |
| Total fixed facility cost | **1828000** |
| Total disposal cost | **500000** |
| Total processing cost | **9945586** |
| Number of products collected | **14285** |

**Table 15 Period-wise comparison of total profit, total revenue and total cost**

| | Period 1 | Period 2 | Period 3 | Period 4 | Period 5 |
|---|---|---|---|---|---|
| Total profit | 446770.0 | 603421.6 | 755141.2 | 289791.9 | 128083.9 |
| Total revenue | 6970150.0 | 6970150.0 | 6970150.0 | 6970150.0 | 6970150.0 |
| Total cost | 6523380.0 | 6366728.0 | 6215009.0 | 6680358.0 | 6842066.0 |

### *5.3 Validation of the proposed multi-period model*

The focus of our work is to develop a unified network design that accommodates variations in input parameters over several time periods. In order to validate the efficacy of the revised model, we consider five different problem scenarios and solve the model in each of this scenario. The input parameter settings in each of this scenario are provided in Table 16. It is found that the facility opening decisions obtained in all the 5 scenarios are the same as that obtained for the unified design (Table 13) provided in Section 5.2. The total profit obtained in all these scenarios is provided in Table 17. Thus, the results validate the efficacy of the proposed model.

**Table 16 Input parameter settings for five different scenarios**

| Scenario | Period | Product return* | Unit transportation cost* | Unit processing cost* |
|---|---|---|---|---|
| 1 | **1** | Base case | Base case | Base case |
| | **2** | 10 % decrease | 10 % decrease | 5 % increase |
| | **3** | 20 % increase | 5 % increase | 10 % decrease |
| | **4** | 10 % increase | 5 % decrease | 10 % increase |
| | **5** | 20 % decrease | 10 % increase | 5 % decrease |
| 2 | **1** | Base case | Base case | Base case |
| | **2** | 10 % increase | 10 % decrease | 5 % increase |
| | **3** | 20 % decrease | 5 % decrease | 10 % decrease |
| | **4** | 10 % decrease | 5 % increase | 10 % increase |
| | **5** | 20 % increase | 10 % increase | 5 % decrease |
| 3 | **1** | Base case | Base case | Base case |
| | **2** | 10 % increase | 5 % decrease | 5 % increase |
| | **3** | 10 % decrease | 10 % increase | 10 % decrease |
| | **4** | 20 % increase | 5 % increase | 10 % increase |
| | **5** | 20 % decrease | 10 % decrease | 5 % decrease |
| 4 | **1** | Base case | Base case | Base case |
| | **2** | 20 % increase | 5 % decrease | 10 % increase |
| | **3** | 10 % increase | 10 % increase | 10 % decrease |
| | **4** | 10 % decrease | 5 % increase | 5 % decrease |
| | **5** | 20 % decrease | 10 % decrease | 5 % increase |
| 5 | **1** | Base case | Base case | Base case |
| | **2** | 20 % decrease | 10 % increase | 10 % increase |
| | **3** | 10 % decrease | 5 % decrease | 10 % decrease |
| | **4** | 10 % increase | 10 % decrease | 5 % decrease |
| | **5** | 20 % increase | 5 % increase | 5 % increase |

*** All changes are with respect to the base case**

**Table 17 Total profit in different scenarios**

| Scenario | Total profit (in INR) |
|---|---|
| 1 | **2217100** |
| 2 | **2218323** |
| 3 | **2222274** |
| 4 | **2215961** |
| 5 | **2214871** |

## 6. Managerial Implications

The business of e-waste processing is witnessing tremendous growth over the past two decades. Companies are trying hard to provide a "green" image to their products. Kodak, Xerox, and General Motors are some of the examples of organizations that succeeded in establishing a strong reverse logistics and recovery activity capability. In developing countries such as India, e-waste recycling is still at a nascent stage. The absence of clear government policies and legal frameworks to deal with the processing of e-waste is an important impediment for large scale investments. In this context, this work has lot of implications for practicing managers. First of all, the development of a network design that can withstand variations in different input parameters over a planning horizon is an important application. Moreover, the problem can be solved to optimality in a reasonable amount of computational time making it amenable for real-life deployment. The provision to incorporate BOM of products into the model helps managers to take advantage of component commonalities and choose the right mix of products for recycling activities. From the results, it can be observed that the transportation costs constitute a significant chunk of the total costs incurred. This implies that a manager is expected to judiciously choose the right mode of transportation between different echelons of the supply chain. The location of collection centres vis-à-vis other facilities has a significant impact on the profits too. In our opinion, locating more number of collection centres with close proximity to remanufacturing centres serves the dual purpose of decreasing the transportation costs and also ensures consistency in product return quantities.

## 7. Conclusions

Enterprises across the globe are spending a lot of time, effort and money to set up their reverse supply chains. A reverse supply chain is made up of a series of activities that are required to retrieve used products from customers, either for disposal or reuse. Reverse supply chains are setup either because of environmental considerations or customer pressures or economic incentives. The main contribution of our study is the development of a generalized mathematical model for the design of a reverse supply chain that can (a) accommodate variations in input parameters over time, and (b) accommodate multiple recovery options simultaneously.

Our model will assist with decisions on the location of reverse logistics facilities while, simultaneously, maximizing profits. Since our model explicitly considers the product BOMs, our expectation is that decision makers will be able to take advantage of component commonalities among different products and analyze the flow at component and material levels between different pairs of entities in the network. This in turn, should enable the decision maker to decide on the usage of appropriate mode of transportation between different facilities of the network. By way of a detailed sensitivity analysis, this work also provides insights into the effect of input parameters on the profit function.

By validating the model with the network design for used refrigerators, we establish its practical relevance. From the results, it is clear that our model is robust enough to accommodate variations in inputs up to a limit of ± 15% in the cost structure and ± 20% in the product return quantity.

## 8. Limitations & Scope for Further Work

The model presented in this work has considered lot of features with practical relevance, while focusing principally on the strategic design of the reverse logistics network. We feel that our work is an important contribution. Nevertheless, there are a few key limitations. Firstly, the model assumes that there is adequate and continuous demand for used products. While this may be true for electronic goods, this assumption may not apply for every used product. Secondly, we have not considered inventory related costs and environmental and social costs while modeling the problem. This is another important limitation. These costs may alter the network design decisions, if accounted accurately. We acknowledge the fact that the inclusion of these costs will make the problem more realistic and help businesses and organizations achieve a more sustainable system. Based on these limitations, we have identified the following four points as possible extensions of this work.

- The model proposed in this work can accommodate uncertainties in input parameters only up to a moderate extent. A logical extension would be to relax the deterministic assumption of input data and develop stochastic optimization models, possibly, based on robust optimization theory to handle uncertainties.
- Developing, preferably, a "linear" model with the explicit consideration of inventory related costs at all the echelons of the supply chain makes the problem more realistic. It helps in studying the effect of inventory related costs on network design decisions.
- Another important extension is the consideration of environmental and social costs. Given the societal pressures and environmental legislations, a network design problem is incomplete with just a profit maximization objective. Developing a framework to analyze each potential network design from a triple bottom line (TBL) framework to assess environmental and social costs will, we believe, be a very good extension.
- Finally, developing closed-loop supply chain models integrating both the forward and reverse logistics networks that encompass the whole gamut of activities starting from raw material procurement to disposal stage (while considering all the aforementioned costs) is an interesting and challenging research problem.

All of the above extensions are difficult to accommodate. We have commenced the study with the base model and expect that further studies will explore the above extensions in greater detail

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## Appendix A

A.1 Distance from collection centres to product return zones, remanufacturing centres and dismantling centres

| | Collection centre | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| Product return zone 1 | 8 | 64 | 105 | 32 | 62 | 85 | 80 |
| Product return zone 2 | 69 | 13 | 57 | 36 | 22 | 25 | 27 |
| Product return zone 3 | 105 | 64 | 9 | 66 | 37 | 38 | 26 |
| Product return zone 4 | 70 | 67 | 55 | 37 | 34 | 61 | 46 |
| Product return zone 5 | 62 | 33 | 52 | 22 | 9 | 35 | 26 |
| Remanufacturing centre 1 | 88 | 76 | 44 | 54 | 41 | 62 | 46 |
| Remanufacturing centre2 | 61 | 75 | 71 | 38 | 46 | 74 | 60 |
| Remanufacturing centre 3 | 97 | 73 | 30 | 60 | 40 | 54 | 39 |
| Dismantling centre 1 | 21 | 85 | 115 | 46 | 75 | 102 | 93 |
| Dismantling centre 2 | 65 | 31 | 49 | 26 | 6 | 30 | 22 |
| Dismantling centre 3 | 63 | 42 | 50 | 24 | 11 | 40 | 28 |
| Dismantling centre 4 | 87 | 52 | 26 | 47 | 20 | 33 | 18 |

A.2 Distance from dismantling centres to recycling centres, repairing centres, secondary markets and to a disposal centre

| | Recycling centre | | | Repairing centre | | | Secondary market | | Disposal centre |
|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 1 |
| Dismantling centre 1 | 33 | 88 | 81 | 86 | 18 | 36 | 39 | 71 | 17 |
| Dismantling centre 2 | 49 | 25 | 23 | 18 | 62 | 64 | 52 | 10 | 71 |
| Dismantling centre 3 | 48 | 37 | 35 | 30 | 59 | 54 | 41 | 5 | 69 |
| Dismantling centre 4 | 72 | 43 | 45 | 35 | 83 | 70 | 58 | 19 | 92 |

A.3 Distance from secondary markets to repairing centres and remanufacturing centres

| | Secondary market | |
|---|---|---|
| | 1 | 2 |
| Repairing centre 1 | 70 | 27 |
| Repairing centre 2 | 45 | 64 |
| Repairing centre 3 | 13 | 59 |
| Remanufacturing centre 1 | 45 | 35 |
| Remanufacturing centre 2 | 14 | 39 |
| Remanufacturing centre 3 | 58 | 36 |

A.4 Distance from recycling centres to primary markets and to a disposal centre

| | Primary market | | Disposal centre |
|---|---|---|---|
| | 1 | 2 | 1 |
| Recycling centre 1 | 66 | 61 | 24 |
| Recycling centre 2 | 39 | 17 | 83 |
| Recycling centre 3 | 40 | 20 | 75 |

A.5 Product return data in the base case

| Product return zone | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Quantity of product return | 660 | 770 | 960 | 620 | 840 |

A.6 Unit transportation cost and unit disposal cost (in INR) of different items

| Item | Unit transportation cost per unit distance | Unit disposal cost |
|---|---|---|
| Refrigerator (collected from product return zones) | 4.5 | |
| Refrigerator (transporting from collection centres) | 3 | |
| Remanufactured refrigerator | 3.5 | |
| Condenser | 0.7 | |
| Cabinet | 1.8 | |
| Compressor oil | 0.6 | 20 |
| Cooling coil | 1 | |
| Refrigerant | 0.8 | |
| Compressor | 1.5 | |
| Ferrous materials | 0.5 | |
| Plastic | 0.5 | |
| Polyurethane foam wastes | 0.8 | 30 |

Table A.7 Capacity, fixed facility cost and unit processing cost of collection centres

| | Collection centre | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| Capacity | 1000 | 900 | 850 | 1000 | 900 | 1050 | 800 |
| Fixed facility cost (INR) | 38000 | 39000 | 37000 | 40000 | 36000 | 44000 | 36000 |
| Unit processing cost (INR) | 62 | 60 | 65 | 53 | 68 | 64 | 57 |

Table A.8 Capacity, fixed facility cost and unit processing cost of dismantling centres and repairing centres

| | Dismantling centre | | | | Repairing centre | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 1 | 2 | 3 |
| Capacity | 1850 | 1500 | 1700 | 1400 | 2200 | 1800 | 1600 |
| Fixed facility cost (INR) | 56000 | 51000 | 54000 | 48000 | 40000 | 38000 | 36000 |
| Unit processing cost (INR) | 174 | 181 | 176 | 186 | 114 | 119 | 112 |

Table A.9 Capacity, fixed facility cost and unit processing cost of recycling centres

| | Recycling centre | | | | | |
|---|---|---|---|---|---|---|
| | 1 | | 2 | | 3 | |
| | Condenser | Cabinet | Condenser | Cabinet | Condenser | Cabinet |
| Capacity | 1500 | 1500 | 2000 | 2000 | 2300 | 2300 |
| Fixed facility cost (INR) | 73000 | | 78000 | | 81000 | |
| Unit processing cost (INR) | 7 | 146 | 7.5 | 155 | 8 | 162 |

Table A.10 Capacity, fixed facility cost and unit processing cost of remanufacturing centres

| | Remanufacturing centre | | |
|---|---|---|---|
| | 1 | 2 | 3 |
| Capacity | 650 | 550 | 900 |
| Fixed facility cost (INR) | 77000 | 72000 | 88000 |
| Unit processing cost (INR) | 1000 | 1020 | 1040 |

Table A. 11 Unit revenue generated (in INR) from markets for different items

| Item | Secondary market | | Primary market | |
|---|---|---|---|---|
| | 1 | 2 | 1 | 2 |
| Remanufactured refrigerator | 4900 | 4950 | - | - |
| Cooling coil | 150 | 160 | - | - |
| Refrigerant | 125 | 120 | | |
| Compressor | 700 | 730 | - | - |
| Ferrous material | - | - | 20 | 21 |
| Plastic | | | 16 | 15 |