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A genetic algorithm approach for solving a closed loop supply chain model: A case of battery recycling

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ABSTRACT

Due to the implementation of government legislation, social responsibility, environmental concern, economic benefits and customer awareness the industries are under a great pressure not only to provide environmentally friendly products but also to take back the product after its use. The issue in reverse logistics is to take back the used products, either under warranty or at the end of use or at the end of lease, so that the products or its parts are appropriately disposed, recycled, reused or remanufactured. In order to overcome this issue, it is necessary to setup a logistics network for arising goods flow from end users to manufacturers. In this study, the optimum usage of secondary lead recovered from the spent lead–acid batteries for producing new battery is presented. The disposal in surface or sewage water or land of liquid content of the lead–acid batteries is strictly restricted. Because of the need for environmental protection and the lack of considerable lead resources, the spent batteries treatment and lead recovery are becoming crucial now-a-days. The objective of this paper is to develop a multi echelon, multi period, multi product closed loop supply chain network model for product returns and the decisions are made regarding material procurement, production, distribution, recycling and disposal. The proposed heuristics based genetic algorithm (GA) is applied as a solution methodology to solve mixed integer linear programming model (MILP). Finally the computational results obtained through GA are compared with the solutions obtained by GAMS optimization software. The solution reveals that the proposed methodology performs very well in terms of both quality of solutions obtained and computational time.

1. Introduction

1.1. Forward supply chain

A forward supply chain is a network of facilities and distribution options that performs the functions of procurement of materials, transformation of these materials into intermediate and finished products, and the distribution of these finished products to customers. Supply chains exist in both service and manufacturing organizations, although the complexity of the chain may vary greatly from industry to industry and firm to firm. Optimizing the supply chain networks in the real world business environment is a very difficult task because the supply chain leader, usually refer to the manufacturer along the supply chain, has to deal with uncertainties in supply and demand with conflicting objectives and tradeoffs along the different elements along the chain.

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1.2. Reverse supply chain

A reverse supply chain focuses on the backward flow of materials from customer to supplier (or alternate disposition) with the goals of maximizing value from the returned item or minimizing the total reverse logistics cost. Rogers and Tibben-Lembke [1] define RL as ‘the process of planning, implementing, and controlling the efficient, cost-effective flow of raw materials, in-process inventory, finished goods and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal’. Reverse distribution can take place through the original forward channel, through a separate reverse channel, or through combinations of both forward and reverse channel.

1.3. Closed loop supply chain

Closed loop supply chain (CLSC) has gained an extensive importance today, in the world of increasing environmental concerns and strict regulations on the wastage caused right from inception of a product, through its life period and after it. A CLSC consists of both the forward supply chain, and the reverse supply chain. The forward supply chain essentially involves the movement of goods/products from the upstream suppliers to the downstream customers. The reverse supply chain involves the movement of used/unsold products from the customer to the upstream supply chain, for possible recycling and reuses. It has been found that reverse supply chain should be a part of forward supply chain integrated, as it can contribute to lowering overall costs and meeting governmental/environmental regulations. Hence, there is a need to model and analyze closed loop supply chains as a system in total, without splitting into distinct parts of forward and reverse supply chains.

1.4. Battery recycling

In case of recycling, products are processed in order to get the desired quality after which they are being reused. The purpose of recycling is to recover the material without conserving any product structures. Examples of recycling are plastic recycling [2], paper recycling [3], glass recycling [4], sand recycling [5], electronic waste recycling [6], carpet recycling [7], and battery recycling [8–13].

Environmental protection and conservation of natural resources has become a great importance at national and international levels. The environmental issue in industrial countries throughout the world is management of hazardous waste. The complex issues depending on social, technical and legislative factors are: how to prevent the environmental deterioration caused by the generation of hazardous wastes, how to minimize the generation of hazardous wastes, and finally how to recover the valuable material contained by the wastes. The present study concerns the recycling of lead–acid batteries (Fig. 1) since waste batteries may be considered as hazardous waste because of their corrosivity, reactivity, or toxicity. Since the birth of the motor car, the lead–acid battery has been dominant in automotive applications. They are used for starting, lighting, and ignition (SLI) service on automobiles and trucks, as well as providing power for automobiles, forklifts, submarines, and almost all other motive vehicles. Even though the principles of operation have remained unchanged, there has been a steady technical improvement in SLI automotive batteries throughout this time. The main components of a lead–acid battery [14] are:

1. Active mass.
   - Anode (negative electrode) consisting of PbO_2.
   - Cathode (positive electrode) consisting of Pb.

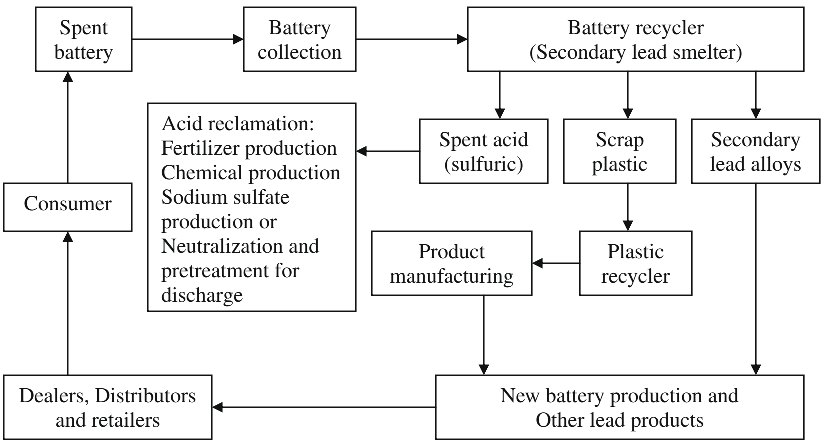

Fig. 1. Lead–acid battery recycling process.

2. Metallic grids, metallic connections.
3. Electrolyte (aqueous solution of H_2SO_4).
4. Polypropylene casing (box).
5. Other components (wood, paper, PVC).

The recycling of batteries has become an increasing attention among the researchers and practitioners in the past few years, due to the increase of vehicles and also the presence of heavy metals such as lead, mercury and cadmium. Compared to 55% of aluminum soft drink and beer cans, 45% of newspapers, 26% of glass bottles and 26% of tires, lead–acid batteries (97% of lead) top the list of the most highly recycled consumer product (Survey from Battery Council International). Lead can be recovered by either separating the different materials that make up the battery (Lead, plastics, acid, etc.) prior to metallurgical processing or batteries can be processed as a whole through heat treatment in a particular type of furnace with metals being recovered at the end of this process. The lead–acid battery gains its environmental edge from its closed-loop life cycle. The typical new lead–acid battery contains 60–80% recycled lead and plastic. When a spent battery is collected, it is sent to a permitted recycler where, under strict environmental regulations, the lead and plastic are reclaimed and sent to a new battery manufacturer. The recycling cycle of spent batteries goes on indefinitely. That means the lead and plastic in the lead–acid battery used in car, truck, boat or motorcycle has been recycled so many times. This makes lead–acid battery disposal extremely successful from both environmental and cost perspectives.

This paper is organized as follows. In the next section, the relevant literature on closed loop supply chain is reviewed. In Section 3, model formulation, assumptions, and model parameters are described in detail; then in Section 4, the solution methodology is proposed. Application of the model to the battery case is discussed in Section 5. Section 6 presents the results and discussion. Finally, in Section 7, conclusions and suggestions for future research are given.

2. Literature review

A major issue in the reverse distribution is integration of forward and reverse supply chain. Returns information captured should be integrated with forward supply chain information to achieve optimum planning and reduction of costs. The whole support network can then be designed in such a way that it can service both the forward and reverse logistics processes efficiently. This is in line with the concept of a closed-loop supply chain design. Many authors have addressed the issues on closed loop supply chain for different case studies.

Fleischmann et al. [15] considered the integration of forward and reverse distribution, and gave a generic integer programming formulation. They took two cases of photocopier remanufacturing and paper recycling, and showed that there was potential for cost savings if one undertook an integrated view rather than a sequential design of the forward and reverse distribution networks. Schultmann et al. [16] developed a hybrid method to establish a closed-loop supply chain for spent batteries. The model included a two stage (collection point-sorting – recycling or disposal) facility location optimization problem. The authors found the optimal sorting centers to open to serve the recycling facilities through a mixed integer linear programming model which minimizes the total cost, and implemented the model in GAMS (General Algebraic Modeling System) and solved it using a branch-and-bound algorithm. As a hybrid method, it also approached to a simulation under different scenarios for a steel making process. Dyckho et al. [17] dealt with the expansion of supply chain to closed loop systems and analyzed the material flow in the automotive cycle. Beamon and Fernandes [18] addressed a closed loop supply chain in which the plants produced new products and remanufactured used products. A multi-period integer programming model was introduced to determine which warehouses and collection centers should be open, and which should have the sorting capabilities and how much was shipped between the sites. Min et al. [19] presented a nonlinear integer program for solving the multi-echelon, multi commodity closed loop network design problem involving product returns. However, their models did not consider temporal consolidation issues in a multiple planning horizon. Chouinard et al. [20] dealt with problems related to the integration of reverse logistics activities into the regular supply chain and to the coordination of information system. Inderfurth [21] focused on a product recovery system where, in the context of extended product responsibility, a manufacturer of original products was also engaged in remanufacturing used products taken back from its customers. For this type of a closed-loop supply chain the optimal recovery and production policy was evaluated. The analysis was restricted to stationary demand and return patterns.

Sheu et al. [22] formulated a linear multi objective programming model to optimize the operations of both integrated logistics and corresponding used-product reverse logistics in a given green-supply chain. Factors such as the used-product return ratio and corresponding subsidies from governmental organization for reverse logistics were considered in the model formulation. The authors also proposed a real world case study for a Taiwan based notebook computer manufacturer. Kumar and Malegeant [23] showed that manufacturer could create value by implementing a partnership with an eco-non-profit community organization in the collection process of used products for the closed loop supply chain. The study focused on the reuse-a shoe program of Nike and the creation of Throwplace.com to point out the benefits of strategic alliances between manufacturers and eco-non-profit organizations. Srivastava and Srivastava [24] developed a conceptual model and an integrated modeling which utilized product ownership data, average life cycle of products, past sales, forecasted demand and likely impact of environmental policy measures to manage product returns for reverse logistics by focusing on estimation of returns for select categories of products in the Indian context. Min et al. [25] proposed a mixed integer non-linear programming model to minimize the total reverse logistics costs for the reverse logistics problem involving both spatial and temporal consolidation of returned products. Kumar and Yamaoka [26] proposed system dynamics (SD) modeling methodology to analyze the closed loop supply chain design for the Japanese car industry. Listes [27] presented a generic stochastic model for the design of networks comprising both supply and return channels, organized in a closed loop system. The author described a decomposition approach to the model, based on the branch-and-cut procedure known as the integer L-shaped method.

Lu and Bostel [28] proposed a two (0, 1) level mixed integer programming model, in which simultaneously forward and reverse flows and their mutual interactions were considered. The problem was formulated as an uncapacitated facility location model and an algorithm based on Lagrangian heuristics was developed. Lee and Dong [29] discussed the logistics network design for end-of-lease computer products and developed a deterministic programming model for systematically managing forward and reverse logistics flows with the objective of minimizing the total cost in the logistics network. Fuente et al. [30] proposed an integrated model for supply chain management (IMSCM) in which the operation of the reverse chain had been built based on the existing processes of the forward chain. Finally the proposed model had been validated in a company from the metal-mechanic sector. Kusumastuti et al. [31] developed a facility location–allocation model for redesigning closed-loop service network at a computer manufacturer. The model considered the possibility of having the network span across several countries and multi-period planning horizons. Sheu [32] formulated a linear multi objective optimization model to optimize the operations of both nuclear power generation and the corresponding induced waste reverse logistics. Factors such as the operational risks induced in both the power generation and reverse logistics processes were considered in the model formulation.

Based on the above literature, it is identified that there is a research potential to make use of closed loop supply chain network for the case of battery recycling (to recover the lead). The purpose of this research work is to develop an integrated, multi echelon, multi period, multi product mixed integer linear programming model to optimize the distribution and inventory level for a closed loop supply chain network using a genetic algorithm. The modeling of this closed loop supply chain network is done in the context of a lead acid battery (SLI batteries) production.

3. Problem description

The company chosen for this study is a battery manufacturing industry located in the southern part of India. The main scope of this study is to estimate the feasibility of reclaiming the lead from automotive batteries. In the forward supply chain, the major raw materials such as lead, plastic, and sulphuric acid are procured from different suppliers for new battery production which is used in two wheelers, four wheelers, and for other industrial applications. Once the battery is produced in different plants it has to be distributed through distributors, wholesalers, retailers and then customers. After its end of life, the automobile owner leaves the used battery at the automobile service station (initial collection point), where it is replaced by a new one. The used batteries collected at the collection points should be quickly transshipped to centralized return center where returned products are inspected for quality failure, sorted for potential repair or recycling. After inspection, the useless batteries (not able to recycle) are disposed off and reusable batteries are transported to disassembly/recycling plants where the batteries are crushed and separated into different components (lead, plastic, acid etc.). Except lead the remaining components are sold to the third party for some other applications (Fig. 1). Finally the recycled lead is transported to the battery manufacturing plants where this secondary lead is used along with the virgin lead for new battery production. The problem addressed here is to built a multi echelon, multi period, multi product closed loop supply chain model to minimize the total supply chain cost comprising procurement, production, distribution, inventory, collection, disposal, disassembly and recycling cost using genetic algorithm.

3.1. Assumptions

The various assumptions involved in this paper are described below.

- The transportation cost per product from the supplier to the manufacturing plant is included in the raw material purchasing cost.
- The daily demand of the customer is deterministic, shortages are not allowed.
- The transportation cost per product from each plant to all distributors, from each distributor to all wholesalers, from each wholesaler to all retailers, from the centralized return center to the disassembly/recycling plant, and from recycling plant to all manufacturing plants remains fixed for all the periods.
- The time taken for transporting the product between the levels is homogeneous and not taken into consideration.
- The inventory carrying cost per product per period at each plant, each distributor, and each wholesaler remains the same throughout the period of study.
- Single unlimited capacity centralized return center (CRC) is maintained by the industry itself.
- The inspection cost per item for the returned products are included in the collection cost.
- The un-recyclable returned products will be sent to the disposal site after some pretreatment process.
- The transportation cost per product from the centralized return center to all disposal sites and pretreatment cost for the disposed products are included in the disposal cost itself.

- It is assumed that except the required recycled component all the remaining components are sold to the third party for some other applications.
- The required recycled materials are assumed to be of the same grade as the virgin raw material bought from the suppliers.
- Logically and economically, a manufacturing plant chooses the raw material from the recycling centers first, then the raw material from the suppliers.
- The lead time of recycled raw material equals the lead time of producing recycled material plus the lead time for transporting the recycled raw material from the recycling center to the manufacturing plant.

3.2. Indices and sets

i	index for raw materials; $i \in I$
s	index for suppliers; $s \in S$
j	index for manufacturing plants; $j \in J$
k	index for distributors; $k \in K$
l	index for wholesalers; $l \in L$
m	index for retailers; $m \in M$
x	index for initial collection points; $x \in X$
y	index for disposal sites; $y \in Y$
z	index for disassembly/recycling plants; $z \in Z$
p	index for products; $p \in P$
t	index for time periods; $t \in T$

3.3. Notations

TC	total closed loop supply chain costs
TPUC	total purchasing costs
TPC	total processing costs
TPDTC	total manufacturing plant to distribution center transportation costs
TDWTC	total distributor to wholesaler transportation costs
TWRTC	total wholesaler to retailer transportation costs
TRMIC	total raw material inventory carrying costs at the manufacturing plant
TFGIC	total finished goods inventory carrying costs at the manufacturing plant
TDIC	total distributor inventory carrying costs
TWIC	total wholesaler inventory carrying costs
TCC	total collection cost of the returned items
TICTC	total initial collection point to the centralized return center transportation costs
TDC	total disposal costs
TCRTC	total centralized return center to disassembly/recycling plant transportation cost
TCICC	total returned products inventory carrying cost at the centralized return center
TRPC	total disassembly/reclaiming cost at the disassembly/recycling plant
TRC	total recycling cost from the disassembly/recycling plant to the third party
TRPTC	total disassembly/recycling plant to manufacturing plant transportation costs
PUC_{ist}	purchasing cost of one unit of raw material '*i*' from supplier '*s*' during time period '*t*'
PC_{jpt}	processing cost per product of '*p*' at manufacturing plant '*j*' at time period '*t*'
$TCPD_{jkpt}$	transportation cost per unit from manufacturing plant '*j*' to distributor '*k*' for product '*p*' at time period '*t*'
$TCDW_{klpt}$	transportation cost per unit from distributor '*k*' to wholesaler '*l*' for product '*p*' at time period '*t*'
$TCWR_{lmpt}$	transportation cost per unit from wholesaler '*l*' to retailer '*m*' for product '*p*' at time period '*t*'
RMI_{ijt}	raw material inventory '*i*' at the manufacturing plant '*j*' during the time period '*t*'
RIC_{ijt}	inventory carrying cost per unit per period of raw material '*i*' at the manufacturing plant '*j*' during the time period '*t*'
X_{ip}	amount of raw material '*i*' required to produce one item of product '*p*'
FGI_{jpt}	finished goods inventory of product '*p*' at the manufacturing plant '*j*' during the time period '*t*'
FIC_{jpt}	inventory carrying cost per unit per period for finished goods of product '*p*' at the manufacturing plant '*j*' during the time period '*t*'
DI_{kpt}	final inventory of product '*p*' at the distributor '*k*' during the time period '*t*'
ICD_{kpt}	inventory carrying cost per unit per period of product '*p*' at the distributor '*k*' during the time period '*t*'
WI_{lpt}	final inventory of product '*p*' at the wholesaler '*l*' during the time period '*t*'
ICW_{lpt}	inventory carrying cost per unit per period of product '*p*' at the wholesaler '*l*' during the time period '*t*'
QC_{xpt}	quantity of returned items of product '*p*' collected at the initial collection points '*x*' during the time period '*t*'
CC_{xpt}	collection cost per item of returned products of '*p*' at the initial collection point '*x*' during the time period '*t*'
$TCIC_{xpt}$	transportation cost per unit from the initial collection point '*x*' to the centralized return center of product '*p*' at time period '*t*'

CI_{pt} returned products inventory of product 'p' at the centralized return center during the time period 't'
DC_{ypt} disposal cost per unit of useless returned product of 'p' to the disposal site 'y' at the time period 't'
$TCCR_{zpt}$ transportation cost per unit of product 'p' from the centralized return center to the disassembly/recycling plant 'z' at time period 't'
ICC_{pt} inventory carrying cost per unit per period for returned products of product 'p' during the time period 't'
QRC_{pt} quantity of returned products of 'p' received during the time period 't'
DR_{pt} disposal rate of product 'p' at time period 't'
DRC_{zpt} disassembly/reclaiming cost per unit for the returned product of 'p' at the disassembly/recycling plant 'z' during the time period 't'
RC_{izt} recycling cost of one unit of raw material 'i' sold to the third party from the disassembly/recycling plant 'z' during the time period 't'
W_p weight of the returned product 'p'
Y_{ip} percentage of contribution of raw material 'i' for the returned product 'p'
$TCRP_{izjt}$ transportation cost per tonne for the required reclaimed raw material 'i' transported from the disassembly/recycling plant 'z' to the manufacturing plant 'j' during the time period 't'
α_{izt} recycling rate of the required raw material 'i' to be reclaimed for new battery production at the disassembly/recycling plant 'z' during the time period 't'
PRS_j raw material storage capacity at the manufacturing plant 'j'
PFS_j finished goods storage capacity at the manufacturing plant 'j'
SC_s supply capacity of supplier 's'
PT_j available processing time in plant 'j'
DSC_k storage capacity of the distributor 'k'
WSC_l storage capacity of the wholesaler 'l'
RSC_m storage capacity of the retailer 'm'
DD_{mpt} demand at the retailer 'm' of product 'p' at time period 't'
CD_{zpt} capacity of the disassembly/recycling plant 'z' of product 'p' at time period 't'
CDS_{ypt} capacity of the disposal site 'y' for product 'p' at time period 't'

3.4. Decision variables

RMP_{isjt} amount of raw material 'i' purchased from supplier 's' to the manufacturing plant 'j' during time period 't'
QP_{jpt} quantity processed of product 'p' at manufacturing plant 'j' during time period 't'
$QTPD_{jkpt}$ quantity transported from manufacturing plant 'j' to distributor 'k' of product 'p' at time period 't'
$QTDW_{klpt}$ quantity transported from distributor 'k' to wholesaler 'l' of product 'p' at time period 't'
$QTWR_{lmpt}$ quantity transported from wholesaler 'l' to retailer 'm' of product 'p' at time period 't'
$QTCD_{ypt}$ quantity of useless returned products of 'p' transported from the centralized return center to the disposal site 'y' at the time period 't'
$QTCR_{zpt}$ quantity of useful (recyclable) returned products of 'p' transported from the centralized return center to the disassembly/recycling plant 'z' at time period 't'
$QPDR_{zpt}$ quantity of returned products of 'p' processed (recycling) at the disassembly/recycling plant 'z' at the time period 't'
RMS_{izt} amount of recycled raw material 'i' from the disassembly/recycling plant 'z' sold to the third party during the time period 't'
$RMRP_{izjt}$ amount of required reclaimed raw material 'i' for new battery production transported from the disassembly/recycling plant 'z' to the manufacturing plant 'j' during the time period 't'

3.5. Mathematical formulation

The objective function of the multi echelon, multi period, and multi product closed loop supply chain model is given by the following equation:

$$\textbf{Minimize TC} = \mathrm{TPUC + TPC + TPDTC + TDWTC + TWRTC + TRMIC + TFGIC + TDIC + TWIC + TCC + TICTC + TDC} \\ \mathrm{+ TCRTC + TCICC + TRPC + TRC + TRPTC}.$$

The cost components in the objective function can be calculated by using the following relations:

- *Purchasing costs* – The total purchasing costs of virgin raw material can be determined as follows:

$$\mathrm{TPUC} = \sum_i \sum_s \sum_j \sum_t (RMP_{isjt} * PUC_{ist}).$$

- *Processing costs* – The total processing costs involved in all manufacturing plants can be determined as follows:

$$\mathrm{TPC} = \sum_j \sum_p \sum_t (QP_{jpt} * PC_{jpt}).$$

- *Transportation costs* – The total transportation costs involved in the forward supply chain include the transportation costs from each manufacturing plant to all distributors, from each distributor to all wholesalers, from each wholesaler to all retailers.
- The total transportation costs from each manufacturing plant to all distributors cab be determined as follows:

$$\mathrm{TPDTC} = \sum_j \sum_k \sum_p \sum_t (QTPD_{jkpt} * TCPD_{jkpt}).$$

- The total transportation costs from each distributor to all wholesalers can be determined as follows:

$$\mathrm{TDWTC} = \sum_k \sum_l \sum_p \sum_t (QTDW_{klpt} * TCDW_{klpt}).$$

- The total transportation costs from each wholesaler to all retailers can be determined as follows:

$$\mathrm{TWRTC} = \sum_l \sum_m \sum_p \sum_t (QTWR_{lmpt} * TCWR_{lmpt}).$$

- *Inventory carrying cost* – The total inventory carrying costs involved in the forward supply chain include the inventory carrying costs of raw material at the manufacturing plant, inventory carrying costs of finished goods at the manufacturing plant, inventory carrying costs at the distributor, and inventory carrying costs at the wholesaler.
- The total inventory carrying costs of handling the raw material inventory at the manufacturing plant can be calculated as follows:

$$\mathrm{TRMIC} = \sum_i \sum_j \sum_t (RMI^*_{ijt} RIC_{ijt}),$$

where $RMI_{ijt} = RMI_{ij(t-1)} + \sum_s RMP_{isjt} - \sum_p (X_{ip} * QP_{jpt}), \quad \forall i \in I, \quad j \in J, \quad t \in T.$
- The total inventory carrying costs of holding the finished goods inventory at the manufacturing plant can be calculated as follows:

$$\mathrm{TFGIC} = \sum_j \sum_p \sum_t (FGI_{jpt} * FIC_{jpt}),$$

where $FGI_{jpt} = FGI_{jp(t-1)} + QP_{jpt} - \sum_k QTPD_{jkpt}, \quad \forall j \in J, \quad t \in T, \quad p \in P.$
- The total inventory carrying costs of handling the inventory at the distributor can be calculated as follows:

$$\mathrm{TDIC} = \sum_k \sum_p \sum_t (DI_{kpt} * ICD_{kpt}),$$

where $DI_{kpt} = DI_{kp(t-1)} + \sum_j QTPD_{jkpt} - \sum_l QTDW_{klpt}, \quad \forall k \in K, \quad t \in T, \quad p \in P.$
- The total inventory carrying costs of handling the inventory at the wholesaler can be calculated as follows:

$$\mathrm{TWIC} = \sum_l \sum_p \sum_t (WI_{lpt} * ICW_{lpt}),$$

where $WI_{lpt} = WI_{lp(t-1)} + \sum_k QTDW_{klpt} - \sum_m QTWR_{lmpt}, \quad \forall l \in L, \quad t \in T, \quad p \in P.$
- *Collection costs* – The total collection costs of returned products at the initial collection points can be determined as follows:

$$\mathrm{TCC} = \sum_x \sum_p \sum_t (QC_{xpt} * CC_{xpt}).$$

- *Transportation costs* – The total transportation costs from all the initial collection points to the centralized return center are calculated as follows:

$$\mathrm{TICTC} = \sum_x \sum_p \sum_t (QC_{xpt} * TCIC_{xpt}).$$

If the transportation between the initial collection points to the centralized return center is treated as a vehicle scheduling problem, then there is a possibility of minimizing the transportation distance using Savings matrix method (explained in Section 3.6) which will reduce the transportation costs considerably.
- *Disposal costs* – The total disposal costs can be calculated as follows:

$$\mathrm{TDC} = \sum_y \sum_p \sum_t (QTCD_{ypt} * DC_{ypt}),$$

where $\sum_y QTCD_{ypt} = (QRC_{pt} * DR_{pt}), \quad \forall t \in T, \quad p \in P.$

- *Transportation costs* – The total transportation costs from the centralized return center to the disassembly/recycling plant can be calculated as follows:

$$\text{TCRTC} = \sum_z \sum_p \sum_t (QTCR_{zpt} * TCCR_{zpt}),$$

where $\sum_z QTCR_{zpt} = (QRC_{pt} * [1 - DR_{pt}]), \quad \forall t \in T, \quad p \in P$ and $QRC_{pt} = \sum_x QC_{xpt} \quad \forall t \in T, \quad p \in P$.

- *Inventory carrying costs* – The total inventory carrying costs of handling the returned products inventory at the centralized return center can be calculated as follows:

$$\text{TCICC} = \sum_p \sum_t (CI_{pt} * ICC_{pt}),$$

where $CI_{pt} = CI_{p(t-1)} + QRC_{pt} - \sum_y QTCD_{ypt} - \sum_z QTCR_{zpt}, \quad \forall t \in T, \quad p \in P$.

- *Reclaiming costs* – The total disassembly/reclaiming costs involved in all the disassembly/recycling plant can be determined as follows:

$$\text{TRPC} = \sum_z \sum_p \sum_t (QPDR_{zpt} * DRC_{zpt}).$$

- *Recycling costs* – The total recycling cost from the disassembly/recycling plant sold to the third party for other applications can be calculated as follows:

$$\text{TRC} = \sum_i \sum_z \sum_t (RMS_{izt} * RC_{izt}),$$

where $RMS_{izt} = \sum_p (QPDR_{zpt} * W_p * Y_{ip}) \quad \forall i \in I, \quad z \in Z, \quad t \in T$ and $QPDR_{zpt} = \sum_p \sum_t QTCR_{zpt} \quad \forall t \in T, \quad p \in P$.

- *Transportation costs* – The total transportation costs from the disassembly/recycling plant to the manufacturing plant can be calculated as follows:

$$\text{TRPTC} = \sum_i \sum_z \sum_j \sum_t (RMRP_{izjt} * TCRP_{izjt}),$$

where $\sum_j RMRP_{izjt} = \alpha_{izt}(1 - RMS_{izt}) \quad \forall i \in I, \quad z \in Z, \quad t \in T$.

The constraints involved in this closed loop supply chain model are as follows:

- Quantity of all type of raw materials received by any plant from all the suppliers should be less than or equal to the storage capacity of that plant

$$\sum_i \sum_s \sum_t RMP_{isjt} \leqslant PRS_j, \quad \forall j \in J.$$

- Quantity processed at any plant of all products should be less than or equal to the finished goods storage capacity of that plant

$$\sum_p \sum_t QP_{jpt} \leqslant PFS_j, \quad \forall j \in J.$$

- Amount of raw material purchased from a particular supplier for all manufacturing plants should be less than or equal to the supply capacity of that particular supplier

$$\sum_i \sum_j \sum_t RMP_{isjt} \leqslant SC_s, \quad \forall s \in S.$$

- Total processing time required to process all product types at a particular plant should be less than or equal to the available processing time

$$\sum_p \sum_t QP_{jpt} \leqslant PT_j, \quad \forall j \in J.$$

- Quantity transported from all plants to a particular distributor should be less than or equal to the storage capacity of that distributor

$$\sum_j \sum_p \sum_t QTPD_{jkpt} \leqslant DSC_k, \quad \forall k \in K.$$

- Quantity transported from all distributors to a particular wholesaler should be less than or equal to the storage capacity of that wholesaler

$$\sum_k \sum_p \sum_t QTDW_{klpt} \leqslant WSC_l, \quad \forall l \in L.$$

- Quantity transported from all wholesalers to a particular retailer should be less than or equal to the storage capacity of that retailer

$$\sum_{l}\sum_{p}\sum_{t} QTWR_{lmpt} \leqslant RSC_m, \quad \forall m \in M.$$

- Total retailer demand should be less than or equal to the total production rate

$$\sum_{j}\sum_{p}\sum_{t} QP_{jpt} \geqslant \sum_{m}\sum_{p}\sum_{t} DD_{mpt}.$$

- Quantity of returned items collected should be less than or equal to the capacity of the disassembly/recycling plant

$$\sum_{x}\sum_{p}\sum_{t} QC_{xpt} \leqslant \sum_{z}\sum_{p}\sum_{t} CD_{zpt}.$$

- Quantity transported from the centralized return center to the disposal site should be less than or equal to the capacity of the disposal site

$$\sum_{y}\sum_{p}\sum_{t} QTCD_{ypt} \leqslant \sum_{y}\sum_{p}\sum_{t} CDS_{ypt}.$$

- Quantity of returned products 'p' processed at the disassembly/recycling plant 'z' should be less than or equal to the capacity of the disassembly/recycling plant.

$$\sum_{z}\sum_{p}\sum_{t} QPDR_{zpt} \leqslant \sum_{z}\sum_{p}\sum_{t} CD_{zpt}.$$

The above mentioned closed loop supply chain model is a generalized model and it can be applied to other products if satisfies the assumptions mentioned in Section 3.1.

3.6. Savings matrix method

Following are the steps of the savings matrix method:

- Identify distance matrix – the Euclidean distance can be computed as follows:

$$\sqrt{(x_A - x_B)^2 -}(y_A - y_B)^2.$$

- Identify savings matrix.
- Rank the savings – the savings are computed for all pairs of customers using the data from the distance matrix. The savings can be determined as follows:

$$S(A,B) = \mathrm{Dist}(A,W) + \mathrm{Dist}(B,W) - \mathrm{Dist}(A,B).$$

The savings are ranked from high to low. The idea is to merge those two customers to the same vehicle, whose merging gives the highest savings.

- Assign customers to vehicles – the pair giving the highest savings is merged first if the capacity is available.
- Sequence customers within routes.

4. Solution methodology

Since this closed loop supply chain problem involves an iterative procedure, the problem requires a computerized optimization procedure. Hence, the non-traditional optimization technique, genetic algorithm (GA) is adopted to solve this problem. Local search based heuristics are known to produce excellent results in short run times, but they are subject to becoming struck in local minima. The traditional methods of optimization and search do not fare well over a broad spectrum of problem domains. Traditional techniques are not efficient when the practical search space is too large.

GA is different from traditional optimizations in the following ways:

- Works with a coding of the parameter set and not the parameters themselves.
- Searches from a population of points and not a single point.
- Uses information of fitness function and not derivatives or other auxiliary knowledge.
- Uses probabilistic transition rules and not deterministic rules.

GA applies a local search operator in an evolutionary framework. The GA starts with a random population of solutions to explore the solution space of a problem. GA generates successive populations of alternative solutions, until a solution that yields acceptable results is found. The various solutions of this family can be seen as samples of the search space. They compete and cooperate through a number of iterations to achieve improvements. The performance of each solution to the problem is evaluated by a fitness function that corresponds to the objective function of the optimization problem. Within the generation of each successive population, there is an improvement in the quality of the individual solutions. In this way a GA can quickly achieve a successful outcome without the need to examine every possible solution to the problem.

4.1. General scheme of GA

There are numerous functions for evaluating the objective criterion to measure an individual's fitness. Countless methods of reproduction and mutation exist. Even the basic processes of birth and death can vary. However, for genetic optimization, the following steps are generally characterized [33].

Initialization: Generate the initial population randomly.
Evaluation: Compute fitness value, which is a measure of how well the individual optimizes the function. Test each individual using the objective function.
Parent selection: Choose pairs of individuals from the population in such a way that those with higher fitness will get more copies.
Reproduction: Generate children from each pairs of parents. Each parent contributes a portion of its genetic makeup to each child.
Mutation: Randomly change a tiny amount of the genetic information in each child. A complete pass through the above steps is a generation. After each generation is complete, a new one starts with the evaluation of each of the children.

4.1.1. Steps in crossover

Initially select two chromosomes X1 and X2 for the crossover operation. The crossover is performed in three steps:

Step 1: Create two temporary matrices 'D' and 'R' as follows:

$$\mathrm{D} = [(\mathrm{X1} + \mathrm{X2}) \div 2],$$
$$\mathrm{R} = (\mathrm{X1} + \mathrm{X2}) \bmod 2.$$

Step 2: Divide matrix 'R' into two matrices R1 and R2:

$$\mathrm{R} = \mathrm{R1} + \mathrm{R2}.$$

There are many possible ways to divide 'R' into R1 and R2 while satisfying the condition.Step 3: Then produce two offspring Y1 and Y2 (new chromosomes) as follows:

$$\mathrm{Y1} = \mathrm{D} + \mathrm{R1},$$
$$\mathrm{Y2} = \mathrm{D} + \mathrm{R2}.$$

4.1.2. Steps in mutation

Step 1: Make a sub-matrix from a parent matrix.
Step 2: Reallocate the commodity for the sub-matrix. The available amount of commodity and demands for the sub-matrix are determined. Use the initialization procedure to assign new values to the sub-matrix such that all constraints are satisfied.
Step 3: Replace the appropriate elements of the parent matrix by new elements from the reallocated sub-matrix Y. Select the chromosome randomly for the mutation process.

The process is repeated with the mutated chromosome as an initial chromosome for the specified number of generations.

5. Test problem

Since there is no benchmark model available for the proposed model in the area of closed loop supply chain, the heuristics based GA algorithm is selected as a solution methodology to solve large size problems. For smaller size problems the GAMS software provides better results but with worst computational time. Some larger-size real-world problems which cannot be solved by GAMS or other commercial software are only solved by the proposed heuristics based GA. The result comparison between GA and GAMS for small-size problems shows that we can trust the heuristics based GA as a solution methodology

Table 1
Test problem size.

Type	Size	Number of products	Number of Distributors	Number of wholesalers	Number of retailers	Number of initial collection centers
I	1-2-2-2-1	1	2	2	2	1
II	1-2-2-2-2	1	2	2	2	2
III	1-2-2-2-3	1	2	2	2	3
IV	1-2-2-2-4	1	2	2	2	4

Table 2
Results obtained by proposed method and GAMS.

Type of problem	Population	Number of iterations	Total cost (Rs.)		Error (%)	Computational time (s)	
			Heuristics based GA	GAMS		Heuristics based GA	GAMS
I	10	50	906,455	885,465	2.37	5	2800
I	25	100	906,093	885,465	2.33	9	2800
I	40	150	902,920	885,465	1.97	12	2800
I	50	200	885,465	885,465	0.00	15	2800
II	10	50	1,055,529	1,016,856	3.80	8	3108
II	25	100	1,045,112	1,016,856	2.78	11	3108
II	40	150	1,041,452	1,016,856	2.42	14	3108
II	50	200	1,027,350	1,016,856	1.03	16	3108
III	10	50	1,665,289	1,550,563	7.40	36	3652
III	25	100	1,664,623	1,550,563	7.36	48	3652
III	40	150	1,658,794	1,550,563	6.98	92	3652
III	50	200	1,652,132	1,550,563	6.55	106	3652
IV	10	50	2,095,425	1,991,245	5.23	156	4245
IV	25	100	2,084,592	1,991,245	4.69	201	4245
IV	40	150	2,077,292	1,991,245	4.32	256	4245
IV	50	200	2,068,950	1,991,245	3.90	314	4245

for the larger problem sizes. The Various test problems, with different sizes, are solved to evaluate the performance of the proposed algorithm. The sizes of the test problems considered for the validation purpose is shown in Table 1. The test problems are solved with different heuristics parameter to test the quality of the solutions obtained through the proposed heuristics based GA. The data set for the test problems given in Tables 1 and 2 is available with the authors. Because of restriction in the number of paper the authors have not given the data in this paper. Interested readers can contact the authors for the data set. The percentage error calculation is calculated using the formula given below.

$$\%\ error = \frac{(GA\ Solution - GAMS\ Solution)}{GAMS\ Solution} \times 100$$

From the above Table 2 it clearly reveals that the proposed heuristics based GA provides closer solution with good computational time. Based on the above solution, we can use proposed heuristic based GA for the large size problems.

6. Application of the proposed model to the battery case study

In this section the mixed integer linear programming closed loop supply chain model is applied to a case of battery manufacturing industry located in the southern part of India.

6.1. An overview of the company

The company chosen for this research work is a famous battery manufacturing industry located in the southern part of India. The company is producing a wide variety of automotive (MHD 800; MHD 600; EK601 etc.), VRLA (5AH; 7AH; 9AH etc.) and other type of batteries used in automobiles and for some industrial applications. There are eight battery industries located in all over India with total employee strength of about 4500 per shift. The turnover of the chosen company for this study is 1200 crore rupees per year having employee strength of about 1000 per shift, operating two shifts per day with two assembly lines. Now the company is under a great pressure to take back the used batteries because of the governmental regulations and also to reduce the total supply chain costs. They planned to recycle the lead (which is the major cost component) from the used battery and thereby used as a raw material for new battery production instead of purchasing the virgin lead material from the supplier. This closed loop supply chain process is used to achieve the minimum total cost.

6.2. Case illustration

The following data was used for validating the multi echelon, multi product, multi period closed loop supply chain distribution inventory model: (see Tables 3a, 3b, 4a, 4b, 5–7)

Number of suppliers = 2.
Type of raw materials = 2.
Number of manufacturing plant = 1.
Number of distributor = 2.
Number of wholesaler = 2.
Number of retailer = 2.
Number of initial collection point = 5.
Number of disposal site = 1.
Number of disassembly/recycling plant = 1.
Disposal rate = 2%.
Recycling rate = 90%.
Crossover probability = 0.7.
Mutation probability = 0.05.
Number of iterations = 200.

Table 3a
Transportation cost/unit in (Rs).

From/To	Distributor		From/To	Wholesaler		From/To	Retailer	
	D1	D2		W1	W2		R1	R2
Plant1	5	6	D1	5	4	W1	4	2
			D2	4	4	W2	3	3

Table 3b
Demand details at the retailer.

Period	Retailer 1		Retailer 2	
	Product A	Product B	Product A	Product B
1	400	350	450	400
2	375	425	425	375

Table 4a
Collection cost and disposal cost details of the returned products.

Product	Collection cost (Rs)		Disposal cost (Rs)	
	Period 1	Period 2	Period 1	Period 2
A	290	300	10	10
B	250	250	8	8

Table 4b
Purchasing cost, inventory carrying cost and lead requirement details.

Period	Purchasing cost of lead/kg (Rs)	Product	Amount of Lead required in kg for 1 unit	Finished goods inventory carrying cost/unit/period (Rs)
1	100	A	10.752	4
2	110	B	6.72	5

Table 5
Production cost and processing time details.

Product	Production cost/unit (Rs)		Processing time (min)
	Period1	Period2	
A	280	300	1.5
B	250	260	1.2

6.3. Savings matrix method

In this case the company is having two trucks each having a capacity of 550 units. Instead of transporting the returned products from each collection point to the centralized return center, the company wants to collect the returned products from all the initial collection points subject to the vehicle capacity limit of 550 units. The centralized return center (CRC) location is taken as (0,0) and the locations of all the initial collection points (ICP) and the corresponding returned product details are given in Table 8. The objective of this vehicle scheduling problem is to minimize the total distance traveled which in turn will reduce the transportation cost.

Step 1: The distance matrix is computed by using Euclidean distances and it is shown in Table 9.
Step 2: Instead of serving two different initial collection points by two different vehicles, if a single vehicle is used to serve both the initial collection points, then some traveling distance is saved. The savings are computed for all pairs of initial collection points using the data from the distance matrix and the savings matrix is shown in Table 10.
Step 3: The savings are ranked from high to low. The idea is to merge those two initial collection points to the same vehicle, whose merging gives the highest savings. From the savings matrix shown on the previous slide, the highest savings of 27.9 is obtained by merging ICP3 and ICP4 to the same vehicle. Next highest savings of 20.9 is obtained by merging ICP1 and ICP3 to the same vehicle. Similarly the other savings are ranked and shown in the Table 11.
Step 4: Merge the initial collection points. The pair giving the highest savings is merged first if the capacity is available. To merge the lowest ranked pair (3,4), the capacity required = 160 + 180 = 340 < 550, the capacity available. So, merge 3 and 4. To merge the next pair (1,3), capacity required = 160 + 180 + 190 = 530 < 550, the capacity available. So, merge 1 and 3 (and 4). Merging (4,5), (3,5), (2,4) and (2,3) requires more capacity than available. The pair (1,4) is already merged. So, the pairs are crossed out. Similarly all the initial collection points are assigned to both the vehicles.

Table 6
Input parameters.

Parameter		Value
Total raw material storage capacity of the plant		30,000 kg/period
Total finished goods storage capacity		5000 units/period
Raw material supply capacity of the supplier		25,000 kg/period
Production capacity		4000 units/period
Disassembly/recycling plant capacity		1500 units/period
Total available processing time for	Product A	4000 min/period
	Product B	3500 min/period
Disposal site capacity		200 units/period
Raw material inventory carrying cost per unit per period		Re.0.5
Transportation cost per product from the CRC to the disassembly/recycling plant (same for all product and all periods)		Rs.3/unit

Table 7
Inventory carrying cost and storage capacity details.

Parameter	Distributors		Wholesalers		Retailers	
	1	2	1	2	1	2
Storage capacities (units/period)	2000	1900	1500	1700	1000	1100
Inventory carrying cost per unit per period	1	2	1.5	1	2	1

Table 8
Returned product details at the initial collection point.

Initial collection point	Co ordinates		Returned products in units			
	X	Y	Period 1		Period 2	
			A	B	A	B
1	0	12	90	100	95	85
2	6	5	160	125	150	135
3	7	15	85	75	90	85
4	9	12	100	80	55	85
5	15	3	115	95	110	120
Total returned products			550	475	500	510

Step 5: Sequencing of initial collection points assigned to the same vehicle: A question is in what sequence will the first vehicle visit ICP1, 3 and 4 and return to the CRC? Similarly, another question is in what sequence the other vehicle will visit ICP2 and 5. This problem is popularly called the traveling salesman problem. The nearest neighbor rule can be used which states that always visit the ICP that is nearest. The only possible sequences of the two vehicles are: CRC – ICP1 – ICP3 – ICP4 – CRC and CRC – ICP2 – ICP5.

7. Results and discussion

In the savings matrix method, the transportation between the initial collection points and the centralized return center was treated as a vehicle scheduling problem, and the corresponding distance between the entities was minimized up to 38.2 km and 32.3 km for vehicle one and vehicle two, respectively, and the corresponding optimum transportation cost was calculated as Rs. 1410. Table 12 displays the various cost components corresponding to the forward, reverse, and closed

Table 9
Distance matrix.

From/To	CRC	ICP 1	ICP 2	ICP 3	ICP 4	ICP 5
CRC	0	12.0	7.8	16.6	15.0	15.3
ICP1		0	9.2	7.6	9.0	17.5
ICP2			0	10.0	7.6	9.2
ICP3				0	3.6	14.4
ICP4					0	10.8
ICP 5						0

Table 10
Savings matrix.

From/To	ICP1	ICP2	ICP3	ICP4	ICP5
ICP1	0	10.6	20.9	18.0	9.8
ICP2		0	14.3	15.2	13.9
ICP3			0	27.9	17.4
ICP4				0	19.5
ICP5					0

Table 11
Ranking of savings.

Rank	1	2	3	4	5	6	7	8	9	10
Merging of ICP	(3,4)	(1,3)	(4,5)	(1,4)	(3,5)	(2,4)	(2,3)	(2,5)	(1,2)	(1,5)

Table 12
Cost components for the forward and closed loop supply chain model.

Supply chain model	Cost components	Optimum cost (Rs)
Forward supply chain	Purchasing cost	33,49,316
	Production cost	8,71,900
	Transportation cost	38,400
	Inventory carrying cost	1,190
	Total cost	42,60,806
Reverse supply chain	Collection cost	5,55,750
	Transportation cost	9,306
	Inventory carrying cost	0
	Disposal cost	370
	Recycling cost	18,010
	Disassembly/reclaiming cost	94,875
	Total cost	6,78,311
Closed loop supply chain	Total cost	28,79,086

loop supply chain model using genetic algorithm. Since the purchasing cost (forward supply chain) was the major cost component in the total cost, the company decided to go for closed loop supply chain.

From the Table 12, it is quite clear that the collection quantity of used batteries is increased by giving some incentives (or) exchange cost (collection cost) for purchasing the new battery. This increased quantity of returned products would lead to reclaim more amount of lead from the used batteries. In the forward supply chain the amount of lead required to produce both product A and B is 15,093.12 kg in period 1 and 13,063 kg in period 2. The amount of lead reclaimed during the recycling process is 8028.117 kg in period 1 and 7765.63 kg in period 2. Since the raw material cost of lead is more compared to the remaining raw material cost, the secondary (reclaimed) lead was used along with the virgin raw material lead for new battery production. This reduced the purchasing cost of lead from the supplier and finally, a 32.4% cost reduction was achieved in this closed loop supply chain model.

8. Conclusion

The environmental concerns regarding the reduction of waste, hazardous material and other consumer residuals together with the economic value of extending the product life cycle provide industries with new and emerging business opportunities. Both environmental and economic objectives can be achieved with the same system by utilizing a closed loop supply chain model. A closed loop mixed integer linear programming model was developed to determine the raw material level, production level, distribution and inventory level, disposal level, and recycling level at different facilities with the objective of minimizing the total supply chain costs. The model is solved by the proposed heuristics based genetic algorithm (GA) and for smaller size problem the computational results obtained through GA are compared with the solutions obtained by GAMS optimization software. For smaller size problems the GAMS software provides better results but with worst computational time. Some larger-size real-world problems which cannot be solved by GAMS or other commercial software are only solved by the proposed heuristics based GA. The result comparison between GA and GAMS for small-size problems shows that we can trust the heuristics based GA as a solution methodology for the larger problem sizes. The solution reveals that the proposed methodology performs very well in terms of both quality of solutions obtained and computational time. Based on the above validation, finally the proposed model in this research was tested with some real data extracted from the battery industry sources and achieved a cost reduction of 32.4% for the battery manufacturing industry by integrating the forward supply chain with the reverse supply chain. The mathematical model is generalized enough to be relevant to most types of OEMs or hazardous material involved manufacturers. Since the model was considered for single objective optimization, in future the multi objective model may be considered. In the present model, only recycling of end-of-life products was concerned. Other possible activities such as product remanufacturing can be added to the model. The probabilistic demand pattern may also be considered in the future study.

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