Closed-Loop Supply Chains for Spent Batteries

Interfaces, 2003, 33, 57-71.

Ji-Su Kim

Production and Logistics information Laboratory
Department of Industrial Engineering
Hanyang University
February, 14, 2012

Contents

Introduction

❖ Introduction

- Scope of research
  - Closed loop recycling networks for spent batteries.
    - Portable batteries command special attention in the field of reverse logistics.
  - The worldwide battery market can be roughly divided into three segments.
    - Starter batteries and large accumulators for industrial purposes.
    - Non-rechargeable (primary) portable batteries.
    - Rechargeable (secondary) portable batteries.

Introduction

❖ Introduction

- Scope of research (continued)
  - Closed loop recycling networks for spent batteries.
    - Collection from the consumer.
    - Sorting the collected batteries.
    - Recovering valuable components from the sorted fractions by using reprocessing techniques.

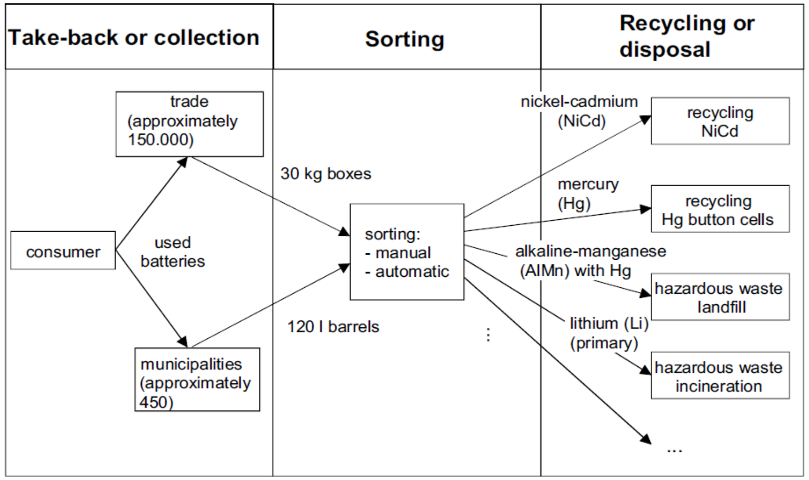

Figure 1. Main steps in closed loop recycling network

Table 1. Status of taken-back (spent batteries)

	Sold (Tons)	Taken Back (Tons)	Rate (Percent)
Primary batteries			
Zinc-carbon	9,952.0	3,404.6	34.2
Alkaline-manganese	16,137.4	4,870.6	30.2
Zinc-air	277.1	251.0	90.6
Lithium	441.1	225.1	51.0
Secondary batteries			
Lithium	430.8	36.0	8.4
Nickel-metal-hydride	1,833.5	17.2	0.9
Lead	519.0	403.3	77.7
Nickel-cadmium	3,214.5	1,000.9	31.1
Button cells	252.9	87.0	34.4
Total	33,058.4	10,295.8	31.1

❖ Literature review

- Related articles

Articles	Specifications
Van Hillegersberg et al. (2001) Guide and Van Wassenhove (2003) Krikke et al. (2003)	Closed-loop supply chains
Fleischmann et al. (1997, 2000) Fleischmann (2001)	Detailed survey of logistic network designs for recovering spent products
Rentz et al. (1999)	Car starter batteries
Krikke et al. (1999)	Copiers
Guide (2000) Flapper et al. (2002)	Rework and remanufacturing

Closed loop recycling model

❖ Two-stage facility location problem

- Problem description
  - Multi-commodity, multi-stage, capacitated facility location problem.
  - The system will require new battery sorting facilities or extensions of the existing facilities.

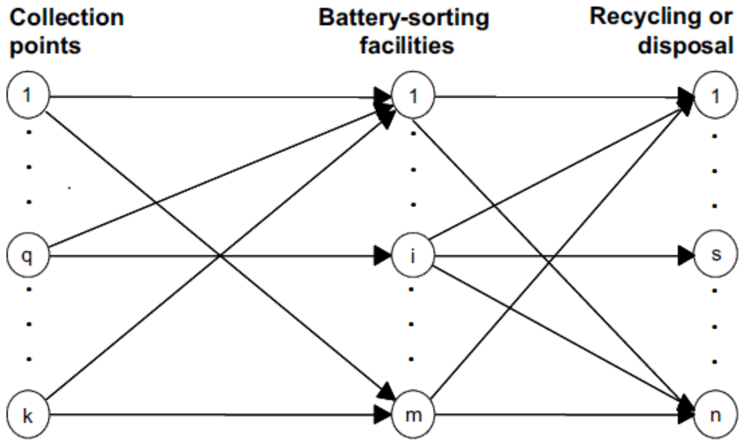

Figure 2. Network structure

✓ Integrate new battery-sorting facilities at new locations.

✓ Increase the capacities of the existing plants (pre-determined capacities).

Closed loop recycling model

❖ Two-stage facility location problem

- Decision variables
  - Which sorting facilities at which locations to open from a given set of potential (additional) locations.
  - Which sorting facilities to expand.
- Objective
  - Minimize total fixed and transport costs.
- Main constraints
  - Capacity constraint (pre-determined capacities).

Closed loop recycling model

❖ Notations

Sets:

Q = the set of sources q, where the batteries are collected,

I = the set of potential locations for battery-sorting units i,

B = the set of battery fractions b arising during the sorting of the collected batteries,

S = the set of recycling or disposal sites s, at which recycling or safe disposal for a battery fraction is possible (sinks),

I_{s1} = the set of locations i, where a battery-sorting unit with the capacity area $\kappa = 1$ is installed,

κ_i = the capacity range of the battery-sorting unit at site i with $\kappa = 1, 2, \ldots, \bar{\kappa}_i$,

$\bar{\kappa}_i$ = the biggest capacity range at site i,

$k^u_{i\kappa}$ = the lower bound of the capacity range κ of the sorting unit at site i,

$k^o_{i\kappa}$ = the upper bound of the capacity range κ of the sorting unit at site i,

J_s = the set of battery fractions j, for which a common maximal capacity exists at the recycling or disposal site s,

B_{sj} = the set of the jth group of batteries that have a common maximal capacity at the recycling or disposal site s,

S_b = the set of recycling or disposal sites s at which sorted batteries of the type b can be recycled or safely deposited.

Parameters:

The objective function contains the following parameters:

c_q = the cost of transport per unit of distance from the source q to the sorting unit i,

$f_{i\kappa}$ = the fixed cost for operating a battery-sorting unit at site i within the capacity range κ,

$c_{i\kappa}$ = the variable cost per unit of weight for sorting a quantity of battery mix at site i within the capacity range κ,

c_{ibs} = the cost of transport per unit of distance for the sorted battery fraction b from the sorting unit i to the recycling or disposal site s,

v_{bs} = the recycling cost per unit of weight for reprocessing sorted battery fraction b at the recycling or disposal site s,

k_s = the capacity of the recycling or disposal site s for the jth group of battery fractions, which implies a common maximal capacity at this site.

To express the restrictions, we used the following parameters:

α_b = the share of battery fraction b of the collected battery mix $(0 \le \alpha_b \le 1)$,

β_{bs} = the minimum share of the battery fraction b, that must be delivered to a recycling site s $(0 \le \beta_{bs} \le 1)$,

a_q = the quantity of batteries collected at source q.

We formulate the planning problem as follows:

Closed loop recycling model

❖ Notations (Continued)

Decision variables:

x_{qi} = the quantity of mixed batteries (in tons per year) transported from the source q to the battery-sorting unit i,

$x_{i\kappa}$ = the quantity processed at the site i within the capacity range κ,

x_{ibs} = the quantity of battery fraction b transported from sorting unit i to recycling or disposal site s,

$y_{i\kappa}$ = the number of battery-sorting units in operation at location i and within the capacity range κ.

Closed loop recycling model

❖ Model formulation

$$\text{Minimize} \quad \sum_{q\in Q}\sum_{i\in I} c_{qi}\cdot x_{qi} + \sum_{i\in I}\sum_{\kappa=1}^{\bar{\kappa}_i}(f_{i\kappa}\cdot y_{i\kappa} + c_{i\kappa}\cdot x_{i\kappa}) + \sum_{i\in I}\sum_{b\in B}\sum_{s\in S_b}(c_{ibs}+v_{bs})\cdot x_{ibs} \quad (1)$$

$$\text{subject to} \quad \sum_{i\in I} x_{qi} - a_q = 0 \quad \forall q\in Q \quad (2)$$

(transporting the collected battery mix from all sources)

$$\sum_{q\in Q} x_{qi} - \sum_{\kappa=1}^{\bar{\kappa}_i} x_{i\kappa} = 0 \quad \forall i\in I \quad (3)$$

(sorting the delivered battery mix in every sorting unit)

$$\alpha_b\cdot\sum_{\kappa=1}^{\bar{\kappa}_i} x_{i\kappa} - \sum_{s\in S_b} x_{ibs} = 0 \quad \forall i\in I,\ b\in B \quad (4)$$

(transporting the sorted batteries to the recycling or disposal sites)

$$\sum_{\kappa=1}^{\bar{\kappa}_i} y_{i\kappa} \geq 1 \quad \forall i\in I_{s1} \quad (5)$$

(preserving the existing battery-sorting units)

$$k_{i\kappa}^{u}\cdot y_{i\kappa} - x_{i\kappa} \leq 0 \quad \forall i\in I,\ \kappa=1,\ldots,\bar{\kappa}_i \quad (6)$$

$$x_{i\kappa} - k_{i\kappa}^{o}\cdot y_{i\kappa} \leq 0 \quad \forall i\in I,\ \kappa=1,\ldots,\bar{\kappa}_i \quad (7)$$

(transporting batteries only to sorting sites with valid capacity ranges)

$$\sum_{i\in I} x_{ibs} - \beta_{bs}\cdot\alpha_b\cdot\sum_{q\in Q} a_q \geq 0 \quad \forall b\in B,\ s\in S_b \quad (8)$$

(minimum delivered quantity to recycling sites)

$$\sum_{\substack{i\in I\\ b\in B_{sj}}} x_{ibs} - k_{sj} \leq 0 \quad \forall s\in S,\ j\in J_s \quad (9)$$

(Maximum recycling capacity is not exceeded.)

$$x_{qi},\ x_{i\kappa},\ x_{ibs} \geq 0 \quad \forall i\in I,\ b\in B,\ s\in S_b,\ q\in Q,\ \kappa=1,\ldots,\bar{\kappa}_i \quad (10)$$

(nonnegativity for the variables x_{qi}, $x_{i\kappa}$, and x_{ibs})

Closed loop recycling model

❖ Model formulation (Continued)

$$y_{i\kappa} \in \mathbb{N} \quad \forall i \in I,\ \kappa = 1, \ldots, \bar{\kappa}_i \tag{11}$$

(Number of sorting units is integer valued and positive.)

$$k^o_{i\kappa} = k^u_{i\kappa+1} \quad \forall \kappa = 1, \ldots, \bar{\kappa} - 1 \tag{12}$$

$$k^o_{i\kappa} \geq k^u_{i\kappa}. \quad \forall i \in I,\ \kappa = 1, \ldots, \bar{\kappa}_i \tag{13}$$

$$k^u_{i\kappa} \geq 0 \quad \forall i \in I \tag{14}$$

(dividing the capacity spectra of the battery-sorting units into technically determined capacity ranges)

$$\sum_{b \in B} \alpha_b = 1 \tag{15}$$

(The sum of the sorted battery fractions equals the collected battery mix.) Condition (15) is valid because misthrows in the collection boxes, such as starter batteries or other wastes, are sorted into a special waste fraction.

$$\sum_{s \in S} \beta_{bs} \leq 1 \quad \forall b \in B. \tag{16}$$

(The sum of the minimum amounts of battery fraction b delivered to the recycling and disposal sites cannot be greater than the amount collected of fraction b.)

$$a_q \geq 0 \quad \forall q \in Q \tag{17}$$

$$k_{sj} \geq 0 \quad \forall s \in S,\ j \in J_s \tag{18}$$

(Nonnegativity for the amount of collected batteries and for the capacities of recycling and disposal sites.)

Case study for spent batteries

❖ Recycling networks for spent batteries in Germany

- Defined two scenarios that have different goals.
- Implemented the model in the software package GAMS and solved it with a branch and bound algorithm.

Table 2. Two scenarios: recycling networks for spent batteries in Germany

	Weight of Batteries Collected (Tons)	Collection Points	Mercury-Free Alkaline-Manganese and Zinc-Carbon Batteries (%)	Potential Sorting Facilities	Recycling Facilities
Scenario 1	11,246	450	10	450 (including 4 existing facilities)	21
Scenario 2	22,492	450	90	450 (including 4 existing facilities)	29 (including 8 EAF)

Case study for spent batteries

❖ Test results

Table 2. Test results for two scenarios

Location of Sorting Facility	Throughput (Tons per Year)	Capacity Utilization (%)	Cost (Million Euros)	
Scenario 1				
Jever	1,246	62.3		
Bremerhaven	2,000	100	Transport	2.83
Grevenbroich	4,000	100	Sorting	1.02
Dietzenbach	4,000	100	Reprocessing or disposal	1.52
Total	11,246	90.6	Total	5.37
Scenario 2				
Jena	4,000	100		
Jever	2,500	62.5		
Bremerhaven	3,992	99.8		
Grevenbroich	4,000	100	Transport	5.60
Dietzenbach	4,000	100	Sorting	1.82
Augsburg	4,000	100	Reprocessing	2.48
Total	22,492	93.7	Total	9.90

- ✓ Existing sorting plants had to stay in operation.
- ✓ The sorting facility in Jever operated at 62 percent of capacity.
- ✓ The other facilities operated at close to capacity.
- ✓ The optimal solution suggests including two new sorting locations, Jena and Augsburg.
- ✓ The optimal solution suggests including two new sorting locations, Jena and Augsburg.

Conclusion

❖ Summary

- Establishing a closed-loop supply chain for spent batteries that combines an optimization model for planning a reverse-supply network.

- Results show that almost complete recycling of spent batteries can be achieved by transforming the current structure into a modified recovery network.

Thank You !

Q and A