MIT ESD

Massachusetts Institute of Technology
Engineering Systems Division

ESD Working Paper Series

Designing Sorting Facilities in Reverse Logistics Systems

Eva Ponce-Cueto
Escuela Técnica Superior de Ingenieros Industriales
Universidad Politécnica de Madrid
Madrid, Spain.
Currently visiting professor at Center for Transportation & Logistics
Massachusetts Institute of Technology
Cambridge, MA, USA
eva.ponce@upm.es, eponce@mit.edu

Edgar E. Blanco
Center for Transportation & Logistics
Massachusetts Institute of Technology
Cambridge, MA, USA
eblanco@mit.edu

Natalia Duque Ciceri
Materials Systems Lab
Massachusetts Institute of Technology
Cambridge, MA, USA
nduquec@mit.edu

This paper was submitted to the 9th International Meetings on Logistics Research (RIRL). Montreal, Canada. August 15-17, 2012

ESD-WP-2012-18 June 2012 esd.mit.edu/wps

Designing Sorting Facilities in Reverse Logistics Systems

Eva Ponce-Cueto
Universidad Politécnica de Madrid, UPM, Spain
MIT Center for Transportation & Logistics[1], USA
(eva.ponce@upm.es, eponce@mit.edu)

Edgar E Blanco
MIT Center for Transportation & Logistics, USA
(eblanco@mit.edu)

Natalia Duque Ciceri
MIT Materials Systems Lab, USA
(nduquec@mit.edu)

Abstract

The main aim of this paper is to propose a multi-waste mix integer lineal programming model for locating sorting facilities in a three-level (local, regional, and central) reverse logistic network. The objective of the model is to decide the location of the storage and sorting facilities across the network. The model was applied in end of life battery recycling network in Spain. As capacity is constrained, the optimal solution moves towards a combination of regional and local facilities for storage and a central facility for sorting.

Key words: Reverse logistics, mixed integer linear programming, battery recycling

[1] Thanks to Caja Madrid mobility grant (2011/12) that financed Professor Eva Ponce-Cueto, research activities at the MIT Center for Transportation & Logistics.

1: INTRODUCTION

Reverse logistics refers to all operations and flows related to recovery products and materials. According to Rogers and Tibben-Lembke (1998) reverse logistics is “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”. Different types of returns such as End of Life (EOL), End of Use (EOU), commercial returns or reusable articles (Carrasco-Gallego et al., 2012) are recovered through these systems. Each type of return requires a reverse supply chain appropriate to the characteristics of the returned products to optimize value recovery (Guide et al., 2003).

In the last two decades this topic has received increasing attention. The growing volume of waste stream (e.g., electronic waste), and the complexity of waste generated (increasing content of toxic substances that pose a threat to human health and the environment), causes that companies, governments, associations, researchers, ecologists, and other social agents, pay special attention to this problem. Social demand for environmental protection has translated into a variety of legal frameworks to tackle this problem. For instance, different EOL European Union Directives based on the Extended Producer Responsibility (EPR) principle require to organize collection and manage of different EOL products such as waste of electrical and electronic equipment (WEEE), end of life vehicles, tires or batteries in an environmentally sound manner.

Logistics systems need to be adapted to these new requirements. This interest goes further than recycling, affecting design and operation of the reverse systems, too. It is a complex problem, as it considers a new type of logistic system that is designed to “close” towards the traditional productive system cycle.

This work focuses on the design of the reverse logistic network for EOL products. The main contribution of this paper is to propose a generic and multi-waste mix integer lineal programming (MILP) model for locating sorting facilities in a three-level reverse logistic network for waste storage and sorting.

The paper is organized as follows. In section 2, the literature review of network design problems in reverse logistics systems is included. In section 3, the description and conceptualization of the problem is presented. In section 4, a generic, multi waste three-level reverse logistic network MILP is proposed. Using this model, a case study for portable used batteries in Spain is described in section 5. Also the results of the model and discussion of these results are included in this section. Finally, in section 6, conclusions and areas of future research are discussed.

2: NETWORK DESIGN PROBLEMS IN REVERSE LOGISTICS

This paper focuses on the design of reverse logistics network for EOL products. Previous studies related to the design, planning, and optimization of product recovery network were conducted by Bloemhof-Ruwaard et al. (1999), Fleischmann et al. (2000; 2001), Krikke et al. (1999), Jayaraman et al. (2003), and Bostel et al. (2005). These models focus on different recovery options (e.g., reuse or remanufacturing), a two-level reverse logistic network and mainly concentrate on location of remanufacturing facilities. For instance, Barros et al. (1998) proposed a two-level location problem applied to the case of sand recycling in the Netherlands. The model used a multi-level capacitated warehouse location model solved by heuristic procedures to find out which facilities should be built and how the sand should be classified, stored, cleaned, and delivered in order to minimize the total cost of the system. Krikke et al. (1999) presented a case study for copiers and proposed a mixed integer lineal programming model (MILP) to optimize the total operation cost of the reverse logistic network (optimal location and flow of goods). Spengler et al. (1997) proposed a MILP model based on a multi-level warehouse location problem for the recycling of industrial by-products in the German steel industry. Jayaraman et al. (2003) proposed a mathematical programming model based on a heuristic solution methodology for choosing an efficient strategy to return defective products to collection sites. They presented a two-level reverse logistic model in which the customer (origination site) returns the product to a retail store (collection site), where the product is then sent to a refurbishing or remanufacturing site (destination site). They assumed fixed collection points and fixed refurbishment and remanufacturing facilities in the reverse distribution network. The objective of the model is to minimize the total cost to transfer products from origination sites through collection sites to the destination facilities and the fixed cost of opening the collection and destination sites.

In this paper, we propose a multi-waste MILP model for locating sorting facilities in a three-level reverse logistic network for storage and sorting and apply it to EOL portable batteries in Spain. Previous models have focused on different recovery strategies and only considered the location of refurbishment or remanufacturing facilities. Not much attention was given to the location of sorting facilities in the reverse logistic network in the literature reviewed. This proposed model fills this increasingly important gap, as reverse logistics networks keep growing around the world. A more detailed description of the three-level reverse logistics network is presented in the following section.

3: THE THREE-LEVEL REVERSE LOGISTICS NETWORK

A reverse logistic system requires the coordination of a series of separate activities and operations in order to manage it in an efficient way. The main activities in a reverse supply chain include (Fleischmann et al., 2000; Guide et al., 2003): collection, storage, sorting, and re-processing (e.g., repair, refurbishing, cannibalization, remanufacturing, and recycling).

Previous authors have focused on the design and location of different facilities in a reverse logistics networks, but no previous studies on selection of sorting facilities and their efficient location along the reverse logistics network have been published.

Different options for storage and sorting waste are possible in a reverse logistics network. A three-level reverse distribution network with local (j), regional (k), and central facilities (l) is considered in this paper (Figure 1). Local facilities may be managed at the municipal/city level, regional facilities may be managed by county, state or autonomous regions while central facilities may be managed by country or continent level. In this reverse logistics network, it is assumed that storage and sorting are allowed at any of these levels. Figure 1 illustrates different waste flow scenarios based on the location of the sorting facilities.

One possible scenario is that unsorted waste flows through each intermediate storage facility and then all collected waste is sorted at the central facility (solid blue line). Note that the central and recycling facilities may be geographically co-located. In another possible network design, the unsorted waste can be sent directly to the central facility in order to be sorted there (solid brown line). In this case the cost of local collection may be higher, but may be offset by not operating local and regional waste collection and storage. Different possibilities, combining local and regional storage with local, regional or central sorting are also possible (represented with dotted lines and different colors).

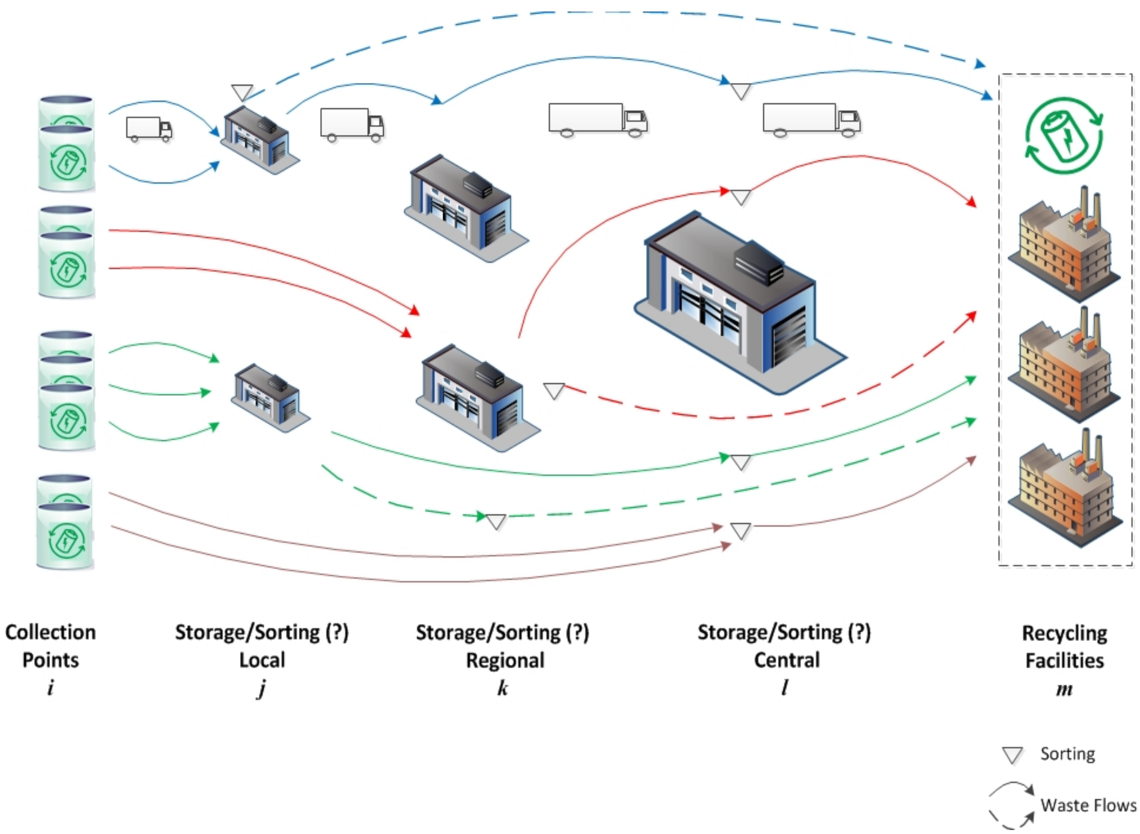

Figure 1. *A three-level reverse distribution network for sorting facilities*

4: MODEL PROPOSED

The model proposed is a generic and multi "waste" model of a three-level reverse distribution network with local, regional, and central facilities. The main purpose of this model is to decide among an array of different facilities if they will be opened or closed, if they will be sorting or just consolidating, and ultimately the flow of sorted waste in the reverse logistics network while minimizing total cost. We assume that all waste must be collected in a single period planning horizon and that recycling facilities are already available to handle the collected waste. Landfilling of collected waste happens at the sorting facility, where waste is classified, or as a by-product of inappropriate waste received at a recycling facility. This model is formulated as a mixed integer linear program (MILP) and is described in next sections.

4.1: Model formulation

4.1.1: Sets, decision variables and parameters

We define the following sets, decision variables, and parameters:

Sets

i – collection points

j – local facilities

k – regional facilities

l – central facilities

m – recycling plants, where m=0 represents the landfill

w – waste types

Decision Variables

$X_{ij}^{w}, X_{ik}^{w}, X_{il}^{w}, X_{jk}^{w}, X_{jl}^{w}, X_{kl}^{w}$ - flow of unsorted waste *w* between collection points (*i*), local facilities (*j*), regional facilities (*k*), and central facilities (*l*).

$\tilde{X}_{jm}^{w}, \tilde{X}_{km}^{w}, \tilde{X}_{lm}^{w}$ - flow of sorted waste *w* from local facilities (*j*), regional facilities (*k*), or central facilities (*l*) to recycling plants (*m*).

$E_{ij}, E_{ik}, E_{il}, E_{jk}, E_{jl}, E_{kl}$ - binary variable that indicates if unsorted waste was sent between collection points (*i*), local facilities (*j*), regional facilities (*k*), and central facilities (*l*).

Y_j, Y_k, Y_l - binary variable that indicates if a local (*j*), regional (*k*), or central (*l*) facility was opened.

Z_j, Z_k - binary variable that indicates if a local (*j*) or regional (*k*) facility is sorting waste. Note that central facilities (*l*) always sort waste, thus no Z_l variable is defined.

Parameters

v_i^w – total volume of waste *w* collected at collection point *i*.

ρ_j, ρ_k, ρ_l - sorting inaccuracy rate of local (*j*), regional (*k*), and central (*l*) facilities. A number between 0 and 1 that indicates the percentage of waste that will be improperly classified at the facility, but still received at the recycling plant (where it will be landfilled).

b_j, b_k, b_l - waste flow capacity (kgs) of local (*j*), regional (*k*), and central (*l*) facilities.

$c_{ij}, c_{ik}, c_{il}, c_{jk}, c_{jl}, c_{jm}, c_{kl}, c_{km}, c_{lm}$- cost (€ per kg-km) of moving waste between collection points (*i*), local facilities (*j*), regional facilities(*k*), central facilities(*l*), and recycling plants (*m*).

$d_{ij}, d_{ik}, d_{il}, d_{jk}, d_{jl}, d_{jm}, d_{kl}, d_{km}, d_{lm}$- distance between collection points (*i*), local facilities (*j*), regional facilities(*k*), central facilities(*l*), and recycling plants (*m*).

f_j , f_k , f_l - fixed cost (€) of operating local (*j*), regional (*k*), and central (*l*) facilities.

s_j, s_k, s_l - fixed cost (€) of adding sorting capabilities to local (*j*), regional (*k*), and central (*l*) facilities.

h_j, h_k, h_l - handling cost (€/kg) received at local (*j*), regional (*k*), and central (*l*) facilities.

h_j^w, h_k^w, h_l^w - handling cost (€/kg) of sorting waste *w* at local (*j*), regional (*k*), and central (*l*) facilities.

β_m - cost (€/kg) of disposing improperly classified waste at recycling pant *m*, for *m*>0. This includes all transportation and treatment to properly landfill from recycling plant.

4.1.2: Objective Function

The objective function is to minimize the total cost of the reverse logistics network. This cost is broken in four main components: facility operation, waste handling, transportation, and disposal. They are defined as follows:

Facility Operation

Includes the fixed and variable costs of operating local, regional, and central facilities:

$$\sum_j \left(f_j Y_j + s_j Z_j \right) + \sum_k f_k Y_k + s_k Z_k + \sum_l f_l Y_l \qquad (1)$$

Waste Handling

Includes the variable costs of receiving and sorting waste at local, regional, and central facilities:

$$\begin{aligned} &\sum_j \left[h_j \left(\sum_{i,w} X_{ij}^w \right) + \sum_{m,w} h_j^w \tilde{X}_{jm}^w \right] + \\ &\sum_k \left[h_k \left(\sum_{i,w} X_{ik}^w + \sum_{j,w} X_{jk}^w \right) + \sum_{m,w} h_k^w \tilde{X}_{km}^w \right] + \qquad (2) \\ &\sum_l \left[h_l \left(\sum_{i,w} X_{il}^w + \sum_{j,w} X_{jl}^w + \sum_{k,w} X_{kl}^w \right) + \sum_{m,w} h_l^w \tilde{X}_{lm}^w \right] \end{aligned}$$

Transportation

Includes all the costs to collect and move waste (sorted and unsorted) through the reverse logistics system.

$$\sum_{i,j} c_{ij} d_{ij} \left(\sum_{w} X_{ij}^{w} \right) + \sum_{i,k} c_{ik} d_{ik} \left(\sum_{w} X_{ik}^{w} \right) + \sum_{i,l} c_{il} d_{il} \left(\sum_{w} X_{il}^{w} \right) +$$
$$\sum_{j,k} c_{jk} d_{jk} \left(\sum_{w} X_{jk}^{w} \right) + \sum_{j,l} c_{jl} d_{jl} \left(\sum_{w} X_{jl}^{w} \right) + \sum_{k,l} c_{kl} d_{kl} \left(\sum_{w} X_{kl}^{w} \right) + \quad (3)$$
$$\sum_{w,j,m} c_{jm} d_{jm} \tilde{X}_{jm}^{w} + \sum_{w,k,m} c_{km} d_{km} \tilde{X}_{km}^{w} + \sum_{w,l,m} c_{lm} d_{lm} \tilde{X}_{lm}^{w}$$

<u>Disposal</u>

Cost of disposing all the improperly classified cost at recycling plants:

$$\sum_{w,j,m>0} \beta_m \rho_j \tilde{X}_{jm}^{w} + \sum_{w,k,m>0} \beta_m \rho_k \tilde{X}_{km}^{w} + \sum_{w,l,m>0} \beta_m \rho_l \tilde{X}_{lm}^{w} \quad (4)$$

4.1.2: Constraints

The following are the model constraints:

$$\sum_{j} X_{ij}^{w} + \sum_{k} X_{ik}^{w} + \sum_{l} X_{il}^{w} = v_{i}^{w} \qquad \forall w, i \quad (5)$$

$$\sum_{i} X_{ij}^{w} = \sum_{k} X_{jk}^{w} + \sum_{l} X_{jl}^{w} + \sum_{m} \tilde{X}_{jm}^{w} \qquad \forall w, j \quad (6a)$$

$$\sum_{i} X_{ik}^{w} + \sum_{j} X_{jk}^{w} = \sum_{l} X_{kl}^{w} + \sum_{m} \tilde{X}_{km}^{w} \qquad \forall w, k \quad (6b)$$

$$\sum_{i} X_{il}^{w} + \sum_{j} X_{jl}^{w} + \sum_{k} X_{kl}^{w} = \sum_{m} \tilde{X}_{lm}^{w} \qquad \forall w, l \quad (6c)$$

$$\sum_{w,i} X_{ij}^{w} \le b_j \qquad \forall j \quad (7a)$$

$$\sum_{w,i} X_{ik}^{w} + \sum_{w,j} X_{jk}^{w} \le b_k \qquad \forall k \quad (7b)$$

$$\sum_{w,i} X_{il}^{w} + \sum_{w,j} X_{jl}^{w} + \sum_{w,k} X_{kl}^{w} \le b_l \qquad \forall l \quad (7c)$$

$$\sum_{j} E_{ij} + \sum_{k} E_{ik} + \sum_{l} E_{il} = 1 \qquad \forall i \quad (8a)$$

$$\sum_{k} E_{jk} + \sum_{l} E_{jl} = 1 \qquad \forall j \quad (8b)$$

$$\sum_{l} E_{kl} = 1 \qquad \forall k \qquad (8c)$$

$$\sum_{w} X_{ij}^{w} \leq M \cdot E_{ij} \qquad \forall i, j \qquad (9a)$$

$$\sum_{w} X_{ik}^{w} \leq M \cdot E_{ik} \qquad \forall i, k \qquad (9b)$$

$$\sum_{w} X_{il}^{w} \leq M \cdot E_{il} \qquad \forall i, l \qquad (9c)$$

$$\sum_{w} X_{jk}^{w} \leq M \cdot E_{jk} \qquad \forall j, k \qquad (9d)$$

$$\sum_{w} X_{jl}^{w} \leq M \cdot E_{jl} \qquad \forall j, l \qquad (9e)$$

$$\sum_{w} X_{kl}^{w} \leq M \cdot E_{kl} \qquad \forall k, l \qquad (9f)$$

$$Z_j \leq Y_j \qquad \forall j \qquad (10a)$$

$$Z_k \leq Y_k \qquad \forall k \qquad (10b)$$

$$\sum_{w} X_{ij}^{w} \leq M \cdot Y_j \qquad \forall i, j \qquad (11a)$$

$$\sum_{w} X_{ik}^{w} \leq M \cdot Y_k \qquad \forall i, k \qquad (11b)$$

$$\sum_{w} X_{il}^{w} \leq M \cdot Y_l \qquad \forall i, l \qquad (11c)$$

$$\sum_{w} X_{jk}^{w} \leq M \cdot Y_k \qquad \forall j, k \qquad (11d)$$

$$\sum_{w} X_{jl}^{w} \leq M \cdot Y_l \qquad \forall j, l \qquad (11e)$$

$$\sum_{w} X_{kl}^{w} \leq M \cdot Y_l \qquad \forall k, l \qquad (11f)$$

$$\sum_{w} \tilde{X}_{jm}^{w} \leq M \cdot Z_j \qquad \forall j, m \qquad (12a)$$

$$\sum_{w} \tilde{X}_{km}^{w} \leq M \cdot Z_{k} \qquad \forall k, m \qquad (12b)$$

$$\sum_{w} X_{jk}^{w} \leq M \cdot (1 - Z_{j}) \qquad \forall j, k \qquad (13a)$$

$$\sum_{w} X_{jl}^{w} \leq M \cdot (1 - Z_{j}) \qquad \forall j, l \qquad (13b)$$

$$\sum_{w} X_{kl}^{w} \leq M \cdot (1 - Z_{k}) \qquad \forall k, l \qquad (13c)$$

$$X_{ij}^{w}, X_{ik}^{w}, X_{il}^{w}, X_{jk}^{w}, X_{jl}^{w}, X_{kl}^{w} \geq 0 \qquad \forall w, i, j, k, l \qquad (14a)$$

$$\tilde{X}_{jm}^{w}, \tilde{X}_{km}^{w}, \tilde{X}_{lm}^{w} \geq 0 \qquad \forall w, j, k, l, m \qquad (14b)$$

$$Y_{j}, Y_{k}, Y_{l}, Z_{j}, Z_{k} \in \{0,1\} \qquad \forall j, k, l \qquad (15a)$$

$$E_{ij}, E_{ik}, E_{il}, E_{jk}, E_{kl} \in \{0,1\} \qquad \forall i, j, k, l \qquad (15b)$$

Constraint (5) guarantees that all waste is collected at a collection point and sent to a facility for further processing. Constraints (6) guarantee that all waste received at a local, regional or central facility flows out to a further downstream facility. Constraints (7) enforce that all flow entering a facility will not exceed its waste processing capacity. Constraints (8) enforce that all unsorted waste stays together as it flows to the next downstream facility. Constraints (9) allow unsorted waste to flow to the corresponding downstream facility. M represents a big number (e.g. $M = \sum_{i,w} d_{i}^{w}$). Constraints (10) guarantee that a facility can only sort waste if it is open. Constraints (11) allow inflow of waste to open facilities while constraints (12) allow outflow of sorted waste only when a facility has sorting capability. Constraints (13) guarantees that unsorted waste will not flow out of a facility that has been configured for waste sorting. Finally constraints (14) and (15) define non-negativity and binary variables respectively.

5: CASE STUDY: EOL PORTABLE BATTERIES IN SPAIN

In this section we use the MILP model presented in Section 4 in a real life case study of end of life portable batteries in Spain. The case study presented is a combination of actual data and cost estimation based on other end of life batteries studies published in the scientific literature. All assumptions made in calculating parameters and cost estimates are outlined below.

5.1: Data collection and parameters estimation

According to the official batteries register published by the Spanish Industry, Tourism, and Trade Ministry (MITYC, 2012), 13,026 tones of portable batteries (including: button cell, standard batteries, and portable accumulators) were sold in Spain in 2010 (this amounts to 342 Million of units sold). Alkaline and saline batteries account for 70% of battery sales in Spain in 2010. Button batteries represent hardly 1% of total sales and secondary portable batteries such as lithium ion, nickel cadmium or nickel metal hydride, represent less than 30% of the total sales. Table 1 includes detailed information about battery types, typical use, weight (tones) sold by each type in 2010 and the percentage of 2010 sales of each type.

Table 1*. Battery sales 2010 in Spain. Source: Industry, Tourism and Trade Spanish Ministry (MITYC, 2012)*

Battery Type	Format	Class	Typical Use	Weight (Ton)	% Of Sales
Alkaline Manganese (AlMn)	Portable	Primary	Radios, torches, cassette players, cameras, toys	8,064	61.9
Zinc carbon (ZnC)	Portable	Primary	Torches, toys, clocks, flashing, warning-lamps	1,009	7.7
Primary Lithium (Li, LiMn)	Portable	Primary	Pocket calculators, photography equip., remote controls and electron.	58	0.4
Mercuric oxide	Button	Primary	Non rechargeable	0	0
Zinc Air (ZnO)	Button	Primary	Hearing aids and pocket paging devices	13	0.1
Silver oxide (AgO)	Button	Primary	Cameras, pocket calculators	9	0.1
Alkaline Manganese (AlMn)	Button	Primary	Small portable equipment	28	0.2
Lithium (Li)	Button	Primary	Photographic equipment, remote controls and electronics	77	0.6
Lithium Ion (Li-ion)	Portable	Secondary	Cellular phones, laptops	2,380	18.3
Nickel Cadmium (NiCd)	Portable	Secondary	Cellular phones	694	5.3
Nickel Metal Hydride (NiMH)	Portable	Secondary	Cellular and cordless phones	504	3.9
Lead Acid (sealed) (PbA)	Portable	Secondary	Hobby applications	104	0.8
TOTAL				**13,026**	

5.1.1: Collection volume

Based on the study conducted by Ponce-Cueto et al. (2011), it is considered that selective collection bins are located in supermarket, malls, public institutions, schools, and recycling centers (called "puntos limpios"). The collection bins on sites are polycarbonate tubes of 40 Kg capacity for retail outlets, supermarkets, and public institutions; 60 Kg for certain malls, and 90 Kg for recycling centers. It is assumed that the bin is full when it is collected. Hence, the total volume of batteries collected at collection points (denoted as *i* in the MILP), is 40 Kg for supermarket, retailer outlet, school or public institution and 60 Kg whenever the collection point is located in a big mall. The total volume of batteries collected at "puntos limpios" is 90 Kg. The planning horizon considered is one year. Based on 2010 actual data, an average frequency of collection for the baseline scenario is estimated as one time per year.

5.1.2: Facility sorting inaccuracy

Most battery sorting is a manual-intensive process. Manual facility sorting accuracy rate is estimated as 0,99. This was confirmed with interviews with a sorting plan manager who confirmed that error rates were almost negligible, less than 1%. However, there are technological systems developed for this purpose. Sorting technology options include X-ray sorting, high-speed-sorting machine photorecognition system, electromagnetic sensor, and machines with electrodynamic sensors. These systems have accuracy rate varying from 95-99% (Bernardes et al. 2004). For the purpose of this case study, a 97% accuracy rate was used when a facility uses technology for sorting.

5.1.3: Facility capacity

The baseline has a total of 31 candidate facilities. All of the facilities are currently opened (i.e., zero fixed opening cost). The capacity for each facility type was estimated as follows:

- Waste flow capacity of the 13 local facility (i) is one ton
- Waste flow capacity of the 17 regional facility (j) is 10 tons
- Waste flow capacity of the central facility (k) is 2,500 tons of batteries (i.e., unlimited)

There is a single recycling facility co-located with the central facility with unlimited recycling capacity.

5.1.4: Transportation costs

Road freight is estimated as a function of distance and load. Table 2 shows freight transportation costs published by the infrastructure ministry of Spain (ACOTRAM, 2012).

***Table 2**. Transportation costs*

Cost Of Moving Waste From/To	Truck Capacity (Ton)	Utilization	Unit Cost (€/Km)	Unit Cost (€/Kg-Km)
Collection point *i* to local facility *j*	2	50%	€ 1.939	0.00097
Collection point *i* to regional facility *k*	2	50%	€ 1.939	0.00097
Collection point *i* to central facility *l*	2	70%	€ 1.385	0.00069
Local facility *j* to regional facility *k*	12	70%	€ 1.311	0.00011
Local facility *j* to central facility *l*	12	90%	€ 1.019	0.00008
Local facility *j* to recycling plant *m*	22	90%	€ 1.237	0.00006
Regional facility *k* to central facility *l*	22	90%	€ 1.237	0.00006
Regional facility *k* to recycling plant *m*	22	90%	€ 1.237	0.00006
Central facility *l* to recycling plant *m*	22	90%	€ 1.237	0.00006

For the transportation from collection bins to sorting facility (i.e., local, regional, central), it is assumed that 2-ton capacity trucks are used, based on the interview conducted with a recycling plant manager with varying utilization factors due to different economies of scope. The utilization rates are estimated based on a conservative approximation of the real data of the case. For example, the 50% utilization rate of a 2-ton capacity truck from a collection bin to a local or regional facility assumes that a truck collects waste from multiple collection points as well as other waste along the way. For the collection bins to a central facility, a higher utilization rate is assumed (70%) as it can collect the same amount, consolidate even more with other types of waste (e.g., larger area of operation) and transport them to the facility, which is further away. Even though there may be only 50% of batteries, it can also collect all the other types of electronic and electrical waste (e.g., fluorescent lamps, computers, etc.) to be taken to the sorting/recycling plant. Larger capacity trucks (12-ton) are assumed for the transportation legs from local facilities to regional and central facilities, with 70% and 90% utilization rates respectively. For the remaining transportation legs, 22-ton capacity trucks with a 90% utilization rate are assumed based on the increased volumes and consolidation from these larger facilities that justify a high-capacity truck.

Street addresses were available for all collection points, facilities and recycling plants. Locations were geocoded using the Python GeoPy(v2.5) module using Google Maps

Geocoder. All geocodes were at least accurate at the postal code level, with over 80% geocoded at the street level. Using the geographical coordinates a great-circle distance calculation was performed between all pair of points using the average great-circle radius of 6,372.795 kilometers. These distances were modified by two scalar factors, a circuity factor and a round-trip factor. A circuity factor of 1.58 was adopted based on the average circuity factor of 61 inter-city distance estimation in Spain (Ballou et al., 2002). A factor of 2 is assumed to account for the round-trip of trucks implying that no freight is carried in the return return transportation leg.

5.1.5: Facility operation

An interview with an industry representative determined that the number of employees in a sorting facility with an annual capacity of 7,500 ton per year, vary from 2 to 4 employees, depending of the batch size and the quality of the batteries received (dirty, oxidized…). It is assumed 3 employees for a central facility, 1.5 employees for a regional, and 1 employee for a local facility. The annual cost, including social security and all taxes and expenses, for one sorting employee is 24,000 Euros per year (Royal Decree, 2011).

According to primary data collected through direct interviews, the average sorting cost to classify the mix of primary batteries collected in Spain is 0.13€/Kg (we assume the same sorting cost for all types of batteries). Table 3 shows the fix and variable cost estimated for sorting waste batteries in local, regional, and central facility. The total cost was calculated assuming that the facility receives 2,000 tonnes of batteries per year. The parameter h_*^w (handling cost (€/kg) of sorting waste at facility *i*, *j*, and *k*) is included in the table.

Table 3. *Sorting cost for EOL portable batteries*

Facility	Nº Of Employees	Cost Per Employee	Fixed Labor Cost (A)	Total Cost [Fixed + Variable] (B)	Estimated Variable Cost (B-A)	Estimated h_*^w (€/Kg)
Local	1	24,000	24,000	260,000	236,000	0.12
Regional	1.5	24,000	36,000	260,000	224,000	0.11
Central	3	24,000	72,000	260,000	188,000	0.10

The handling cost for waste received is estimated to 0.10 €/Kg in a central facility, 0.11€/Kg in a regional facility, and 0.12€/Kg in a local facility.

5.1.6: Technology cost

For the option of facilities to use technology for battery sorting, an annual periodic cost has been assumed based on an initial investment of a full-scale battery sorting system. A manufacturer of such system, reports total costs in the order of € 2.7 M- € 4 M. This cost also includes subsequent processes (e.g., accumulation of batteries). The annual periodic cost is calculated at €180,000 - €270,000, assuming 20-year equipment lifetime and a 3% annual interest rate. For the purpose of this study, the higher-end, € 270,000 is assumed.

5.1.7: Disposal cost

The cost (€/kg) of disposing of improperly classified waste (β) at recycling facilities includes treatment and transportation to landfill. The disposal of generated waste takes place in the city city of Madrid and this cost is currently 57€/m^3 (i.e., secure landfill in the city of Madrid) in addition to 8€/ton for landfill tax. Secure landfill costs vary according to their density. The lower the density, the more maintenance the landfill requires; therefore the costs increase at lower densities. The batteries density is assumed to be approximately 1.5ton/m^3, which results results in a disposal cost of treatment of 46€/ton (or 0.046€/kg) including tax. This cost falls within the same order of magnitude of the cost of industrial waste elimination to landfill published by the government of the autonomous community of Aragon (BOA, 2011). The transportation cost related with this activity is estimated the same way transportation figures were explained in section 5.1.4, using a 22-ton truck at 90% utilization. It is assumed that this activity is not exclusive to batteries waste and other wastes are consolidated at the same time to justify the larger truck utilization. In terms of distance, Bilbao to Madrid is assumed, which which is approximately 600 km resulting in a cost of 0.036€/kg. The disposal cost parameter is then the combination of treatment and transportation, which results to be 0.082€/kg.

5.2: Results

This section shows the results of the optimization of the MILP formulation for the baseline and for various sensitivity scenarios. The model was created using the Python (v2.7) PuLP modeling library (v1.5) and solved using IBM ILOG CPLEX (v12.4). All reported solutions are optimal.

5.2.1: Baseline Scenario

All data of the baseline scenario described in section 5.1. Using the model proposed in section section 4, an optimal solution was found to minimize the total cost associated to facility operation, waste handling, transportation, and disposal for the Spanish battery three-level reverse logistics network. Table 4 summarizes the results for the baseline scenario. As shown in Table 4, the optimal solution is: 35 collection bins sent to a regional storage facility where sorting takes place. A single bin (located in the outskirts of the city) leverages transportation economies of scale, and battery waste is stored in a local facility before being sent to the common regional facility for sorting.

***Table 4**. Summary of results for baseline scenario*

Flow Id	Waste Flow	Number of Bins	Total Waste (kgs)	Alk. Waste (kgs)
1	Bin ➔ Regional Sorting ➔ Recycling	35	1,490	1,226
2	Bin ➔ Local ➔ Regional Sorting ➔ Recycling	1	40	32

The total cost for this scenario is 36,348 euros, with a variable cost of 348 euros. Transportation cost represents 26.1% of the total variable cost and holding cost represents almost 25.5% of the variable cost. It is important to highlight that in the baseline scenario, regional facilities have enough capacity (10 tons) to handle all the recycled waste for this case study (1.5 tons).

A detailed description of distances travelled by batteries and operation costs associated to the baseline solution for each of the flows of the optimal solution is shown in Table 5. The average distance traveled for one bin to an intermediate storage facility is 15.4 km, but regional facilities service collection bins as far as 100 km away.

***Table 5**. Detailed description of results for baseline scenario.*

Flow Id	Flow Segment	Average distances (Km)	Minimum distance (Km)	Maximum distance (Km)	Transportation Cost (€)	Holding cost (€)
1	Bin ➔ Regional Sorting	15.4	0	100.3	25.9	84.1
	Regional Sorting ➔ Recycling	743.1	743.1	743.1	63.6	0.0
	Total for Flow 1	758.5			89.5	84.1
2	Bin ➔ Local	29.0	29.0	29.0	0.8	2.4
	Local ➔ Regional	128.0	128.0	128.0	0.5	2.2
	Total for Flow 2	157.0			1.3	4.6
	GRAND TOTAL	915.4			90.8	88.7

5.2.2: Sensitivity analysis

To illustrate various three-level reverse logistics networks, two more scenarios are presented. In the first scenario, collected waste was increased ten-fold. For the second scenario, the relative fixed cost of processing waste between regional and central facilities was also changed, such that central facilities are more efficient in manual sorting operations (i.e., regional facilities need two full time employees instead of 1.5). Tables 6 shows the scenarios results.

Table 6. *Summary of flows for scenarios*

Scenario	Flow Id	Waste Flow	Number of Bins	Total Waste (kgs)	Alk. Waste (kgs)
1	1	Bin ➔ Regional 1 Sorting ➔ Recycling	23	9,200	7,528
	2	Bin ➔ Regional 2 Sorting ➔ Recycling	11	5,301	4,398
	3	Bin ➔ Local 1 ➔ Regional 1 Sorting ➔ Recycling	1	400	328
	4	Bin ➔ Local 2 ➔ Regional 2 Sorting ➔ Recycling	1	400	328
2	1	Bin ➔ Regional 1 ➔ Central Sorting ➔ Recycling	23	9,200	7,528
	2	Bin ➔ Regional 2 ➔ Central Sorting ➔ Recycling	11	5,301	4,398
	3	Bin ➔ Local 1 ➔ Central Sorting ➔ Recycling	1	400	328
	4	Bin ➔ Local 2 ➔ Central Sorting ➔ Recycling	1	400	328

The scenarios illustrate different structures of the reverse logistics network. In scenario 1 (ten- fold volume), the sorting still happens at the regional level, but due to capacity constraints, an additional location is opened for regional storage and sorting. Two bins need to go through a local facility to leverage reduced transportation costs (even if more handling is required). In scenario 2 (ten-fold volume and higher regional fixed sorting costs), the two regional facilities are now used only for storage and all sorting activities are done at the central facility.

5.3: Discussion of results

As expected, the two scenarios yielded different three-level network configurations. The optimal solutions of the baseline case and the first scenario ended up with two-level reverse network with all sorting occurring at regional facilities. The second scenario optimal solution included the central facility for sorting. Table 7 shows the scenario total costs compared to the baseline case.

Table 7. *Sensitivity analysis. Comparison among different scenarios*

	Transportation Cost	Holding Cost	Sorting Cost	Inaccuracy Cost	Total Variable Cost	Fixed Cost	Total Cost
Scenario Baseline	91.0 (26.1%)	86.6 (24.9%)	168.3 (48.3%)	2.4 (0.7%)	348.3 (100%)	36,000.0	36,348.3
Scenario 1	872.4 (25.1%)	889.6 (25.6%)	1,683.1 (48.5%)	24.4 (0.7%)	3,469.4 (100%)	72,000.0	75,469.4
Scenario 2	875.5 (21.7%)	1,608.6 (40.0%)	1,530.1 (38.0%)	12.2 (0.3%)	4,026.5 (100%)	72,000.0	76,026.5

As shown in Table 7, transportation costs are always around 20%-25% of the total variable costs. Regarding holding costs, scenario 2 where the three tiers are fully used, they represent a larger share of the variable cost (40%) compared to the baseline and scenario 1 results (approx. 25%). However, the share of sorting and inaccuracy costs for Scenario 2 is lower due to economies of scale at central facility.

As capacity is constrained at local and regional facilities, optimal solutions tend to fully leverage the three-tier network structure. This explains why nowadays, where excess capacity is available for battery recycling in Spain, a one or two tier reverse network is the common storage and sorting configuration. As volumes grow (e.g., increased recycling rates), the configuration of sorting locations across the three-tier reverse logistics network becomes more complex and with a larger set of candidate options.

6: CONCLUSIONS AND FUTURE EXTENSIONS

In this paper, a MILP model for locating the sorting facilities in a three-level reverse logistic network for storage and sorting is proposed. The objective of this model is to minimize the total cost related to facility operation, waste handling and sorting, transportation, and disposal.

The MILP model was applied to configure the reverse logistics network for portable end of life batteries recycling in Spain. The optimal solution was a two-tier network, were all sorting was done in a single regional facility. Two scenarios were created to illustrate alternative optimal configurations when volumes and fixed sorting costs change. Results indicate that as capacity is constrained and central facilities are more efficient than regional facilities, a three-tier network where sorting is done centrally, is optimal. The MILP model was shown to trade-off handling, sorting and transportation costs in order to design an efficient reverse network with local, regional and central facilities for EOL batteries.

This model could be applied to other EOL returns, especially when a large mix of waste streams is collocated at collection points (e.g., municipal solid waste). The model could be used to further analyze tradeoffs in transportation cost (e.g., increased fuel cost), holding and sorting technologies, open/close facility costs, and varying landfill environments (e.g., increased regulation and penalties for improper disposal).

The model proposed in this study focuses on minimizing cost. Possible extensions include multi-criteria models (e.g., environmental life cycle assessment vs. costs) to analyze environmental impacts and their related trade-offs, as well as optimization techniques for solving large-scale networks.

7: REFERENCES

ACOTRAM (2012) Asistente para el Cálculo de Costes del Transporte de Mercancías por Carretera. Published by the infrastructure ministry of Spain. Retrieved from http://www.fomento.gob.es/MFOM/LANG_CASTELLANO/DIRECCIONES_GENERALES/TRANSPORTE_POR_CARRETERA/SERVICIOS_TRANSPORTISTA/DESCARGA_SOFTWARE/Acotram.htm [April 13, 2012]

Ballou, R.H., Rahardja, H., Sakai, N. (2002), Selected country circuity factors for road travel distance estimation. *Transportation Research Part A: Policy and Practice*, Vol. 36, N°9, pp. 843-848.

Barros, A.I., Dekker, R., Scholten, V. (1998). A two-level network for recycling sand: A case study. *European Journal of Operational Research*, Vol. 110, pp. 199-214.

BOA (2011), Boletin Oficial de Aragon. Retrieved from http://www.boa.aragon.es/cgi-bin/EBOA/BRSCGI?CMD=VEROBJ&MLKOB=604166480404 [March 28, 2012]

Bostel, N., Dejax, P., Lu, Z. (2005). The design, planning, and optimization of reverse logistics networks, i*n* Langevin A., Riopel (Eds.), *Logistics systems: Design and optimization*, Springer, pp. 171-252.

Bernardes, A.M., Espinosa, D.C.R., Tenorio, J.A.S. (2004), Recycling of batteries: a review of current processes and technologies. *Journal of Power Sources*, Vol. 130, N°1–2, pp. 291-298.

Bloemhof-Ruwaard, J.M., Fleischmann, M., van Nunen, J. (1999). Reviewing distribution issues in reverse logistics, *in* Speranza M.G., Stahly P. (Eds.), *New trends in distribution logistics*, Springer-Verlag, Berlin, pp.23-44.

Carrasco-Gallego, R., Ponce-Cueto, E., Dekker, R. (2012). Closed-loop supply chains of reusable articles: a typology grounded on case studies. *International Journal of Production Research*, in press. DOI:10.1080/00207543.2011.649861.

Fleischmann, M., Krikke, H.R., Dekker, R., Flapper, S.D.P. (2000). A characterization of logistics networks for product recovery. *Omega*, Vol. 28, Nº. 6, pp. 653-666.

Fleischmann, M., Beullens, P., Bloemhof-Ruwaard, J.M., van Wassenhove, L.N. (2001). The impact of product recovery on logistics network design. *Production and Operation Management*, Vol. 10, Nº. 2, pp. 156-172.

Guide, V.D.R., Harrison, T.P., Van Wassenhove, L.N. (2003). The challenge of closed-loop supply chains. *Interfaces*, Vol. 33, Nº. 6, pp. 3-6.

Jayaraman, V., Patterson, R.A., Rolland, E. (2003). The design of reverse distribution networks: models and solution procedures. *European Journal of Operational Research*, Vol. 150, pp. 128-149.

Krikke, H.R., van Harten, A., Schurr, P.C. (1999). Business case Océ: Reverse logistics network re-design for copiers. *OR Spektrum*, Vol. 21, Nº. 3, pp. 381-409.

MITYC (2012). Ministerio de Industria, Turismo y Comercio. Registro de Pilas, Baterías y Acumuladores. Retrieved from http://www.mityc.es/industria/pilas/Paginas/Inicio.aspx. [March 19, 2012].

Ponce-Cueto, E., González-Manteca, J.A., Carrasco-Gallego, R. (2011). Reverse logistics for used portable batteries in Spain. An analytical proposal for collecting batteries, *in* Golinska, P.; Fertsch, M. and Marx-Gomez, J. (Eds.), *Information Technologies in Environmental Engineering. New trends and challenges*, Springer-Verlag, Berlin, pp. 593-604.

Rogers, D.S., Tibben-Lembke, R.S. (1998). *Going backwards: Reverse logistics trends and practices,* Reverse Logistics Executive Council Press. Council of Logistics Management, Pittsburgh, PA.

Royal Decree (2011). Real Decreto 1888/2011 por el que se fija el salario mínimo interprofesional para 2012. Retrieved from http://www.empleo.gob.es/es/informacion/smi/contenidos/RD188811.pdf. [March 21, 2012].

Spengler, Th., Püchert, H., Penkuhn, T., Rentz, O. (1997). Environmental integrated production and recycling management. *European Journal of Operational Research*, Vol. 97, pp. 308-326.