Design of Reverse Logistics Network for Waste Batteries with an Application in Turkey

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The demand for portable electronic devices grows everyday and the batteries that power them pose important environmental problems. Batteries contain heavy metals such as; lead, mercury, cadmium that can contaminate the environment when batteries are disposed of improperly. The question is "How to manage this large amount of waste batteries?" In order to minimize the negative impacts of batteries on the environment, legislations have been published in the last two decades. In Turkey, the Regulation on Control of Waste Batteries and Accumulators APAK is published in 2004 and the project 'Development of Waste Battery Disposal and Recycling Technologies' is in progress. Within the scope of the project we do research on logistics of waste batteries. A multi period mixed-integer linear programming (MILP) model is developed to design the reverse logistics network for waste batteries. We solved the model with the objective of minimizing the total present value of waste battery management system under a variety of scenarios in order to provide an effective decision support tool and offer useful outputs to decision-makers.

1. Introduction

In recent years, there is a growing interest to incorporate sustainability in the decision-making process due to increasing environmental consciousness. An important consideration is to protect the environment while conserving and reusing scarce resources. Towards this goal, recycling is one of the most important mechanisms for conserving and reusing these natural resources. We can prevent waste of potentially useful materials and green gas emissions, save energy, reduce pollution, conserve natural resources and help sustain the environment for future generations through recycling.

Waste batteries are identified as a problem for both environment and human body. Batteries contain various chemical substances to store and deliver electrical power. Some of these substances are harmful to the environment and they require substantial resources (energy, water and time) to extract from the mines. For a sustainable world we should re-use the valuable materials after recovering them and dispose unusable parts properly. The waste battery management has become a compelling research problem that integrates technical, environmental and economic issues. Besides general waste electrical and electronic equipment regulations and hazardous waste legislations, many countries have their national legislation for disposal of waste batteries. The common purposes of these legislations are to improve the environmental performance of batteries and minimize the negative impact of batteries on the environment. Every country tries to develop a sustainable way for waste battery management.

In European Union, Battery Directive, 2006/66/EC (EC, 2006) on batteries and accumulators and repealing Directive 91/157/EEC (EC, 1991) is published on 6 September 2006. It aims to improve concord of batteries with environment by limiting the amount of dangerous substances in batteries. Besides, quota application is imposed both for collection and recycling of waste batteries and quotas are determined. Every country in Member States has authorized organizations to provide an effective waste battery management system. In Turkey, the Regulation on Control of Waste Batteries and Accumulators was published in 2004. In order to fulfill the requirements of the Regulation, Turkey strives to develop an efficient mechanism for waste batteries. In addition to the Regulation's requirements on battery collection and recycling, the construction of the first waste battery recycling plant reveals new variables to the system and makes it more complex. Reverse logistics is the main tool for the appropriate management of all types

of waste. Efficient planning and execution of reverse logistics provides sustainable and profit-generating strategies. From environmental point of view, reverse logistics contributes hazardous waste reduction, alleviation of landfilling, and conservation of raw materials. In addition, despite it is not the main goal of reverse logistics, it provides more cost-effective systems. The interest in RL is piqued in the last two decades and a considerable number of research from different points of views have been conducted with the aim of constituting effective and efficient systems for return flows. Recently, Steffen Wolfer, Harald Sander, and Frank Gogoll (2011) discussed the physical configuration of the reverse logistics, recovery and disposal of waste electrical and electronic equipment (WEEE). They proposed a MILP model for locating processing facilities and transporting waste that are in different recovery levels along the links of the network at minimal cost due consideration of legal developments. Some authors focused on the development of an integrated model of a closed-loop supply chain. Lu and Bostel (2007) have developed a two-level specific facility location model for remanufacturing network design considering both forward and reverse flows. Nur Indrianti and Aldila G. Rustikasari (2010) presented a sustainable profit maximization model for reverse logistics in battery manufacturing in Indonesia that considers both environmental and economic aspects.

In Turkey, with the increasing concern on waste batteries, the reverse logistics network optimization of waste batteries becomes more significant. The decision- makers and/or the management should have decision tools to analyze the whole system under different scenarios.

In this paper, a mixed-integer linear programming (MILP) model is presented for the design of reverse logistics network of waste batteries. We solved the proposed model under a variety of scenarios. This study aims to provide an effective decision support tool for decision makers.

2. Reverse Logistics Network Design Model

A mathematical model is developed to model reverse logistics network for waste batteries over a specified planning horizon. The network consists of a set of sorting facilities, recycling facilities, export agencies and landfill areas. Three disposal options are considered for waste batteries; recycling, export and disposal at a landfill area. The formulation developed is a multi period Mixed-Integer Linear Programming (MILP) model.

The model was programmed and implemented in GAMS (General Algebraic Modeling System) optimization package and solved using the CPLEX solver.

In Figure1, we present the general waste battery management network we use. This network includes five nodes, representing waste battery collection nodes, battery sorting facilities, landfill areas, export agencies and recycling facilities. We considered 81 provinces of Turkey as collection points and determined six random provinces as potential locations for sorting facilities and three random provinces for establishing recycling facilities. We assumed that 6 potential sorting facilities to cover all of 7 regions of Turkey. Also, 3 additional potential locations for landfill areas are added to evaluate the behavior of the system in view of combined facilities and separate facilities.
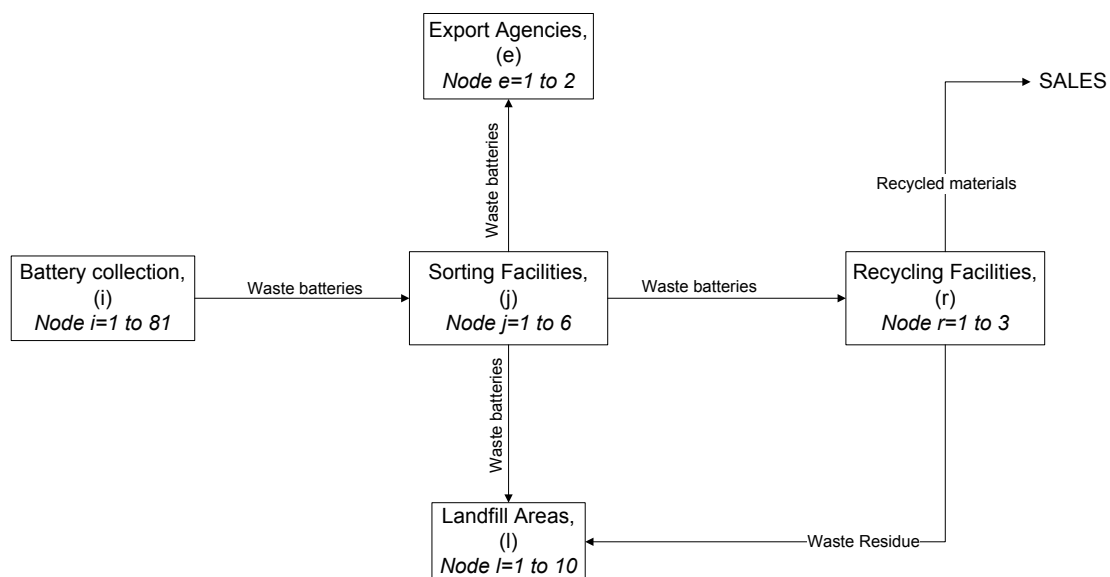

Figure 1: Network representation

The network design of the model demonstrated in Figure1 is based on a reverse logistics (RL) system. Reverse logistics is a notion that is not too old. In the beginning of nineties, firstly Stock (1992) and then Kopicki et al. (1993) recognized the 'Reverse Logistics'. In the last two decades, reverse logistics became an area of increasing concern and a large number of articles published that consider 'Reverse Logistics' from different points of view.

Several different definitions of reverse logistics are stated by various authors and organizations such as Rogers and Tibben-Lembke (1998), Lu and Bostel (2007), The European Working Group on Reverse Logistics Reverse. Considering our setting and all previous definitions we define reverse logistics as management of all operations related to recovery of end of life products and materials which particularly deals with opposite flows from end-users to producers with the aim of capturing value and proper disposal. In this system, reverse logistics actors are end-users, municipalities, private industry, schools, institutions, sorting facilities, etc. Reverse logistics processes are; collection, sorting, selection, reprocessing (recycling or land filling).

As all battery chemistry requires a different battery recycling process, all waste batteries collected in collection nodes are transported to a sorting facility. At sorting facilities, all collected batteries are identified and sorted according to their chemistries. The decision made at these facilities is whether to send sorted waste batteries to a landfill area, an export agency or a recycling facility. At recycling facilities, additional processing is done to separate waste battery into recyclable and non-recyclable (Tchobanoglous et al., 1993). After recycling, the recycled materials are sold and non-recycled part is sent to a landfill area.

3. Model Assumptions and Mathematical Features

In our model we did not consider the cost of collection. Collection amounts are obtained from Portable Battery Manufacturers and Importers Association and assumed constant over planning horizon in the base model. The landfill areas have cumulative stock capacity and there are no flow capacities for these facilities. We permit economies of scale in sorting and recycling operations. There is construction lead time for recycling facilities. Initially, there is not any constructed recycling facility, which leads to transfer all batteries collected to a landfill area in the first year, due to the construction lead time. Market prices of recycled materials are assumed to be constant over the planning horizon, due to the lack of data.

All unit costs and prices are constant over time. In the base case, the composition of batteries collected is assumed to be equal and also constant over planning horizon. We defined 5 different technologies all one which can process different types of materials. The model decides which technological feature should be added with the objective of minimizing cost. Due to the complexity of battery recycling processes, we defined technology modules 1 to 5. Technology5 is taken as the most advanced technology that is able to process all materials, and Technology1 is the least advanced one.

The objective function of the network design model is to minimize the total present value of the cost. The total cost of the system comprise the summation of transportation cost, sorting cost, recycling cost, landfill cost and inventory cost, minus revenues from the sale of recycled materials. The revenues from the sale of recycled materials are added to the objective function as a negative cost. The objective function used in mathematical model is defined as:

Minimize

$$\sum_t \left(\frac{1}{1+r} \right)^t \left(COST_t - REVENUE_t \right) \tag{1}$$

where r represents discount factor.

$$COST_t = TransportationCost_t + SortingCost_t + \mathrm{Re}\,cyclingCost_t + LandfillCost_t + InventoryCost_t \tag{2}$$

$$REVENUE_t = EconomicValueofMaterials_t \tag{3}$$

Transportation cost is proportional to the distance travelled between node pairs. Every year management makes an annual contract with some of the potential sorting facilities. The cost occurred for sorting activity is a linear function of the quantity of waste battery transferred from the waste battery collection nodes and as well as there are cost of making contract with a sorting facility. At recycling facilities, the total cost comprise the cost of new construction, fixed and variable operating and maintenance costs and cost of additional processing technology. Each battery chemistry requires a different recycling process, as each process is designed to recover the particular materials in that battery type. The model decides the feature

of recycling facility by determining which processing technology will be added to a facility. In our model, management can hold recycled material inventory and/or waste battery inventory at recycling facilities. Due to the capacity limitations of recycling facilities, model decides holding inventory in some situations. Also, if market prices are variable over time, holding recycled material inventory can be cost effective.

3.1 Different Scenarios

Three different scenarios are considered in the model which change some of assumptions made for the base model. We solved the proposed model using different cost functions for some facility operations and used new parameters according to the scenarios. We compared the difference in the share of recycling and landfill options and the difference in the selected recycling facility features by the optimization model. For the analyses, we ignored export option, due to the lack of data. Also, excluding export option provide better understanding of the relation between landfill and recycling options.

3.1.1 Scenario 1

Different cost functions reveal alterations in decision as our objective is minimizing the total present value of the cost. Our aim is to analyze the impacts of different cost functions, battery collection amount and composition on the proposed optimization model. We considered three different cost functions for landfill operations. The first function has constant return to scale (CRTS). Total landfill area operating cost is a linear function of the quantity of waste batteries or/and waste residues landfilled. For the second case, unit cost of landfill operations drops gradually after specified quantities which is depicted in Figure 2 which is currently implemented in Turkey. In the third case, we assume that unit landfill operation cost increases with declining remaining capacity of landfill area (Figure3). We solved the proposed model several times with these different landfill cost functions and observed the results. Our aim is to evaluate different cost functions of landfill operations and their results on waste battery management system.
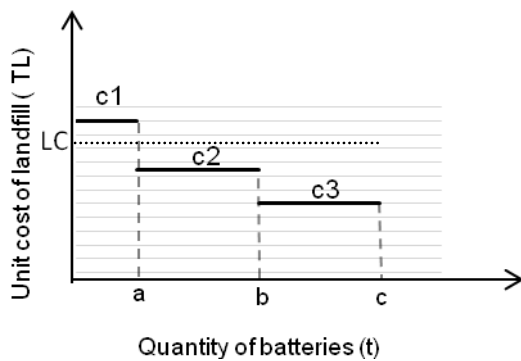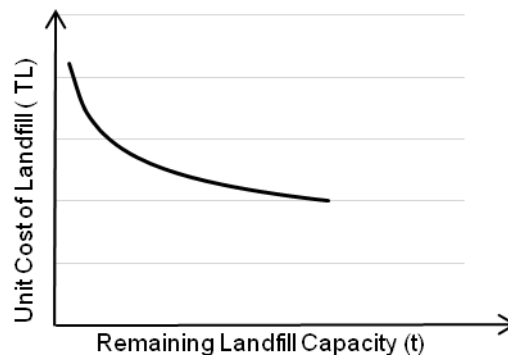

Figure 2: Landfill cost function 1&2   Figure 3: Landfill cost function 3

Three landfill functions are presented in Figure2 and Figure3.

  (i) Case 1- Landfill cost function with CRTS

In the base model we use landfill cost function with constrant return to scale. Considering the first cost function which is shown in Figure1 as dotted line, the total cost of landfill operations is given by

$$\sum_{l} LC_l \times X_{lt} \tag{2}$$

where X_{lt} is the quantity of waste batteries transferred to the landfill area and LC_l is the unit cost of landfill operations.

  (ii) Case 2- Landfill cost function with discounts

We used disjunctive programming to model the second cost function.
Disjunctive model:

$$LCost_{lt} = c1_{lt} \times x1_{lt} + c2_{lt} \times x2_{lt} + c3_{lt} \times x3_{lt} \tag{3}$$

$$\begin{bmatrix} LCost_{lt} = X_{lt} \times c1_{lt} \\ 0 \le X_{lt} \le a \\ y_{l,1,t} \end{bmatrix} \vee \begin{bmatrix} LCost_{lt} = X_{lt} \times c2_{lt} \\ a \le X_{lt} \le b \\ y_{l,2,t} \end{bmatrix} \vee \begin{bmatrix} LCost_{lt} = X_{lt} \times c3_{lt} \\ b \le X_{lt} \le c \\ y_{l,3,t} \end{bmatrix}$$

$$X_{lt} = x1_{lt} + x2_{lt} + x3_{lt}$$

$$y_{l,1,t} + y_{l,2,t} + y_{l,3,t} = 1$$

(iii)   Case 3- Landfill cost function depending on remaining landfill capacity

In Figure 3, the third cost function of landfill operations is given. Here, the unit cost of landfill operations is a function of the remaining landfill capacity and it is inversely proportional to remaining capacity of landfill area. The total cost of landfill operations for a given time period t is given by

$$LCost_t = \sum_l X_{lt} \left(\frac{LCAP_l}{R\_LCAP_{lt}} \right)^{\upsilon}$$ (4)

where $LCAP_l$ is the initial capacity of landfill area l and R_LCAP_{lt} is the remaining capacity of the landfill area at time period t and υ is taken 0.25 (which must be between 0 and 1). Eq(4) makes the objective function nonlinear, hence for this case only we used nonlinear programming solver.

3.1.2 Scenario 2
In the base model, we used the waste battery collection date obtained from TAP. Scenario 2 assumes that every province of Turkey increases its collection and reaches the highest one's collection. This rises the yearly collection amount approximately three times the amount used in base model with a increasing rate of 207.7 %. This scenario tests the impact of economies of scale on recycling operations.

3.1.3 Scenario 3
In the base model, the collected waste battery composition is assumed to be same due to the lack of data. Here, we gathered waste battery composition data from different countries. Europe's leaders in battery collection are determined as Belgium, Germany and Netherlands. GRS Batterien is the common waste battery collection system of Germany which organizes the collection, transportation adn propoer disposal of waste batteries. The annual report 2011 of GRS Batteries depicts that the share of collected primary batteries are 82.5 % while secondary batteries are only 17.5 %. Based on this data, we increased the collected share of primary batteries and decreased the share of secondary batteries.

4. Results and Discussion

The base model and the scenarios are programmed and implemented. The results are given in Table1.

Table 1: Results

SCENARIOS	Scenario1 Landfill Cost Function			Scenario 2 Collection Amount	Scenario 3 Battery Composition
	Function1 (BaseCase)	Function2	Function3		
Recycling share (%)	36.0	26.5	39.2	78.2	43.5
Landfill share (%)	64.0	73.5	60.8	21.8	56.5
Technology	3	3	3	3	5

The analyses conducted with the scenarios are used to determine the impact of changes in landfill cost function, waste battery collection amount and composition on waste battery recycling policy. It is seen that landfill cost function changes the share of recycling and landfilling options. The first cost function is same as the function used in the base model. In the second case of Scenario 1, using the second cost function 73.5 % of batteries collected are landfilled. The batch size of waste batteries transferred to the landfill area is also increased when we used cost discounts after specified amounts. In the third case, the recycling

share of waste batteries is increased from 36 % to 39.2 % of batteries collected. While in the base case, the unit cost of landfill operations does not depend on remaining capacity of landfill area, in this case we assumed that unit cost of landfill operations increase with declining remaining capacity. Using the function, the share of recycling rises compared to the base case. Landfill areas can be considered as scarce sources and it is obvious that landfills are not ideal solution for waste batteries. We claim that cost function alterations can be used as a recycling promotion if management considers it necessary.

In Scenario 2, we observe that in our process economies of scale works. This points out the significance of promoting waste battery collection. For Scenario3, the share of recycling and landfill operations varies by different composition of battery types. In this case, the total cost of the system highly depend on the relation between battery composition, unit revenue obtained from battery types and technological feature required for battery types. In our base case, the amount of all types of batteries is considered to be equal. In this last scenario, by a different composition of batteries, technology 5 is added to the recycling facility which is most advanced one. It is seen that collected waste battery composition is critical while constructing a recycling facility. National data on waste battery collection amounts and composition for all provinces are required for establishing an efficient waste battery management system.

5. Conclusions

In this paper, we present a mixed-integer linear programming model for the design of reverse logistics network that includes collection, sorting, export, recycling and disposal of waste batteries at a landfill area. The features of the model are illustrated and a number of case studies are examined. We are currently applying this study to real-life case of waste battery management in Turkey. As a developing country, Turkey is in a struggle for developing an effective waste battery management system with increasing demand for batteries. TÜBİTAK (The Scientific and Technological Research Council of Turkey) and The Ministry of Environment and Urban Planning pledged to make a sizable investment for the design and construction of a battery recycling plant integrated with the national waste battery collection system. In order to benefit from this investment at the expected level, we offer an efficient decision support tool for the optimization of reverse logistics network for waste batteries.

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