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RESEARCH ARTICLE

A bi-objective model for sustainable logistics and operations planning of WEEE recovery

Emine Nisa Kapukaya [a], Alperen Bal [b], Sule Itir Satoglu [a]*

[a] *Department of Industrial Engineering, Istanbul Technical University, Turkey*
[b] *Department of Industrial Engineering, Yalova University, Turkey*
eminenisacann@gmail.com, alperenbal@live.com, onbaslis@itu.edu.tr

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ABSTRACT

The Triple-bottom-line concept suggests that firms must consider the environmental and social impacts of their decisions, beside the economic aspects. Hence, the sustainability of the firms' operations can be reached. The purpose of this study is to develop a bi-objective, multi-product and multi-period mixed-integer model for the operations planning of electrical-electronic waste (WEEE) recovery facilities, by considering social (workforce) constraints. Main objective is the minimization of net recycling and logistics costs offset by the profit earned by recovered material sales, and second objective is the maximization of hazardous materials recovery. Collection of used products from the specified regions is decided and the required machine-hours, inventory and workforce decisions are made. Besides, both weight-based and unit-based WEEE recovery targets are separately considered, as a unique aspect. A sensitivity analysis is conducted with various scrap prices to understand operations planning in changing conditions. Results show that weight-based targets enhance recovery amounts.

1. Introduction

In today's world, because of the rapid increase in consumption of the commercial products, the natural resources are depleting. Therefore, many countries search for new natural sources or intend to reuse the existing ones. Waste materials that are recovered and recycled may provide a solution for this problem. In accordance, the paradigm has now become "cradle-to-cradle" waste management by means of evaluation, recycling and reuse of the end-of-life products' wastes [1].

The term of Triple-bottom-line (TBL) first proposed by Elkington [2], suggests that firms must consider the environmental and social impacts of their decisions, in addition to the economic aspects. Hence, the sustainability of the businesses can be achieved. Nikolaou et al. [3] also mentioned that companies must have social responsibility beside their profitability targets.

The reverse logistics (RL) enhances the application of the TBL approach, and concerns flow of end-of-life products to the special facilities for recovery of the waste material. The formal definition is as follows: "Reverse Logistics is the process of planning, implementing, and controlling the efficient, effective inbound flow and storage of secondary goods and related information opposite to the traditional supply chain direction for the purpose of recovering value or proper disposal." [4]. In this context, sustainability, as defined by its TBL factors of economic, environmental, and social dimensions is the underlying framework that we use in this study, during the reverse logistics and operations planning [5].

In this study, especially the Cooling and Freezing (CFC) product wastes are considered, because according to the report of the United Nations University, by the application of European Union's 2002 WEEE Recovery Directive, from the estimated 36 million tons of avoided CO emissions, 34 million tons results from removing CFC based cooling agents [6]. Therefore, CFC recovery is the most remarkable issue in WEEE recovery.

The purpose of this study is to develop a bi-objective, multi-product and multi-period mixed-integer model

*Corresponding author

for the sustainable operations planning of WEEE (especially refrigerator) recovery facilities, by considering social (workforce) constraints. Main objective is the minimization of net recycling and logistics costs offset by the profit earned by recovered material sales, and second objective is the maximization of hazardous materials recovery. Based on the region distances and amount of WEEE, whether to collect used products from the specified regions is decided and the required machine-hours, inventory and workforce decisions are made. Besides, both weight-based and unit-based WEEE recovery targets are separately considered, in different scenarios, as a unique aspect. A sensitivity analysis is conducted with various scrap prices to have better understanding of the operations planning in changing conditions.

The paper is organized as follows: The driving forces of WEEE recovery are discussed in Section 2. Later, the most relevant reverse logistics studies are reviewed. In Section 4, the bi-objective model is proposed and explained. In Section 5 , a real life application of the proposed model for reverse logistics operations planning of a refrigerator recovery plant is explained that shows applicability of our study. The Results are discussed in Section 6. An extensive Sensitivity Analysis is performed to analyze the impact of uncertainty in scrap prices and recovery cost of hazardous wastes. Finally, the Conclusion is made.

2. Driving forces of WEEE recovery

Development of third world countries led to increase in the consumption, so some of the natural sources and raw materials are expected to be depleted soon. Reusing these sources will provide a new dimension to this problem. In some developed countries, waste management and prevention are being pursued with legal legislations. These directives also put obligations on issues such as how much the product must be recycled.

Firms are collecting end-of-life products especially because of the legislations. Since the reverse logistics have complex structure and processes are hard to implement, it is rather challenging for the firms to make profit from RL. Establishing an efficient RL network is very costly when considering the small amount of profit, it provides (if any). In some developing countries, the periodically applied 'bring old take new one' campaigns are implemented mainly to increase the market share of the company, not to reuse or recycle the products. Since there is not any financial penalty in legislations, environmental obligations are also not very encouraging. Driving force for RL is not the economy; legislations and environmental concerns are the factors that make RL compulsory.

2.1. Economy

Many developed countries put legislations to increase the returned and recovered end-of-life product amount [6-8]. Other developing countries are also working on these types of legislations[9-10]. Being prepared for these legal obligations in advance is a step that can provide superiority to other firms. Improving the firms' image can be one of the indirect contribution of the RL. Direct and indirect incomes, sales of the materials obtained and the cost reduction in energy are the economic gains.

2.2. Legislations

There has to be legal legislations to force the firms to recover the waste. With obligations, public should be made aware of the importance of the collection of recyclable wastes. Legislation will set certain standards and companies will have to follow up on collection, disposal, recycling, and marketing their products. Many companies in developing countries have accelerated their recycling activities due to new sanctions that will come with directives.

2.3. Environmental concerns

To minimize the negative impacts of waste, proper management strategies should be followed. By reusing, recycling and remanufacturing the WEEE, social and environmental benefits are obtained at the same time. In addition, green company image and advanced customer supplier relationship are profitable for the firms. Environmental issues that are considered in logistics are nonrenewable resources, gas emissions, density and road use, noise pollution, destruction of both harmful and harmless wastes. Besides, CO emission reduction by means of WEEE recycling was reported as much as 36 million tons [11].

3. Literature review

In this section, mathematical modeling studies in RL are discussed. As there are several papers in this field, interested readers can refer to the literature review papers. Especially, Fleischman et. al. [12] reviewed the quantitative models of distribution, production planning, and inventory control in the reverse logistics field. Later, Ilgin and Gupta [13] examined environmentally conscious manufacturing and product recovery papers published between 1998 and 2010. Agrawal et al. [14] reviewed advances in reverse logistics, especially RL studies and perspectives. Recently, Govindan and Soleimani [15] made a review about the reverse and closed-loop supply chain studies.

We would like to mention a few important RL papers and books, here. Hu et al. [16] proposed a cost minimization model recovery of multiple types of hazardous wastes, in multiple discrete time periods. Besides, e-waste types are defined and legislations and the incentives to increase the amount of returned WEEE were discussed [17]. Kumar et. al. [1] examined the closed loop supply chain with SWOT analysis, especially in the successful industry segments, such as, automotive, consumer appliances and electronic and showed the effect of the legislations upon them. Bal et.

al. [18] analyzed WEEE recovery data of Turkey, by neural networks and ANOVA. Kahhat et. al. [19] investigated the WEEE recovery practices and factors affecting the e-waste return in USA. Contributions of OR to the green logistic are mentioned and discussed with many aspects; such as transportation, inventories, supply chain design and planning [20]. Now, the studies pertaining the Single-Objective Models and Multi-objective models are discussed.

3.1. Single-objective models

In this sub-section, single-objective models developed after year-2000 are mentioned. Shih [21] developed a cost-minimization model for reverse logistics planning of WEEE and computers, in Taiwan in 2001. Listes and Dekker [22] created deterministic and stochastic MILP location-allocation models and two-stage and three-stage solution approaches were applied. Stochastic and deterministic models were compared with each other. Additionally, Listes [23] proposed a generic two stage closed loop supply return network model and the L-shape method to maximize the net revenue based on a stochastic approach.

El-Sayed et al. [24] suggested a single objective, multi period multi echelon closed loop supply chain model and the effects of mean demand and return ratio changes were evaluated. Problem was formulated by a Stochastic Mixed Integer Linear Programming (MILP). Furthermore, Achillas et. al. [25] also formulated a MILP model for WEEE collection based on the existing facilities supply chains. Dondo and Mendez [26] developed a cost-minimization model for planning of forward and reverse logistics activities. Recently, Pedram et al. [27] formulated a model to design a closed-loop supply chain including facility location and material flow decisions by maximizing the total profit.

3.2. Multi-objective models

The RL is naturally a multi-objective problem where the environmental and economic aspects must be considered. In addition to these factors, the social aspect is also important. Therefore, there is an increasing number of RL literature with multiple objectives.

Tuzkaya et. al. [28] proposed a model with two objective functions and performed an application in white good industry in Turkey. First objective function aimed to minimize the net cost and the second one maximized the amount of weighted product assigned to the centralized return centers from the initial collection centers. A Genetic Algorithm was applied to solve the problem. Ahluwalia and Nema [29] proposed a multi-objective model for recovery of the computers based on life-cycle assessment. Later, the same authors developed a multi-time-step multi-objective decision-support model minimizing the cost, environmental risk, socially perceived risk and health risk at the same time to decide the optimum waste collection locations [30].

In the model of Ramezani et al. [31], different parameters such as price, production costs, operating costs, collection costs, disposal costs, demands and return rates are assumed to be uncertain. ε-constraint method was used to generate a set of Pareto-optimal solutions for solving this three-objective problem. Objectives of the model were maximizing the total profit, maximizing the customer service level and minimizing the defected products that are provided by suppliers.

A bi-objective, single period, non-linear model was reformulated as a MIP [32]. Environmental protection level was described for the first time in the literature. The model aimed to minimize total cost and total CO emission within the supply chain. Türkay et. al. [33] modified the traditional aggregate production and operations planning approach by considering the environmental and social dimensions, based on the TBL perspective.

A closed loop facility location model was proposed by Amin and Zhang [34] in a supply chain network with multiple facilities and multiple products, and was solved by weighted sums and ε-constraint methods. Authors shown that ε-constraint method provided more efficient solutions. After uncertainties in demand and returns taken into account, it was solved with a scenario-based stochastic programming model.

Another multi-objective MIP model was proposed for location-routing with three objective functions by Samanlioglu [35]. Objectives were minimizing total cost, total transportation risk of hazardous materials and site risk. Ene and Ozturk [36] developed a bi-objective model for network design of recovery facilities of the end-of-life vehicles where maximization of the revenue and minimization of the pollution due to recovery operations were aimed.

To sum up, there is an increasing number of multi-objective RL studies in the literature. However, most of them were deterministic. To the best of authors' knowledge, in none of the deterministic studies, a sensitivity analysis was performed. This is a contribution of our study to the literature.

4. Proposed bi-objective model

The assumptions for proposed bi-objective model are presented as follows :

Additional workforce always exists, when needed.

The manufacturer does not have to collect products from every region; if it can reach the given goal by collecting goods from some of the regions.

There is no capacity limit for inventory and the demand of the secondary market of recovered material is unlimited.

Collected refrigerators are directly transferred to the RL facility.

The disposal cost of harmful materials includes the cost of transportation.

The amount of the material obtained from the recycling of the product is directly proportional to the weight of the product.

Machine process times are deterministic.

Recycle facility location is already determined.

This model answers the following questions:

1. How much is the company's net gain when it reaches the target collection numbers or how much does it cost if it has loss?

2. How much of the harmful wastes to be properly disposed are sent to the licensed firms?

3. In which period (month), from which region, how much product will be collected?

4. When and how much capacity increase is needed(if any)?

5. What are the inventory levels and required labor sources?

4.1. Indices

i: $Product\ index\ (i \in I)(i = 1{,}2)$

b: $Geographical\ regions\ \ index\ (b \in B)(= 1, .., 7)$

t: $Periods\ index (Months)\ (t \in T)(t = 1, .., 12)$

j: Recovered material index (j∈J)(j = 1, .., 9)

m: Machine index $(m \in M)(m = 1, .., 6)$

S: $Subset\ of\ hazardous\ materials\ (S \subset J)(= 7{,}8)$

4.2. Decision Variables

$$Y_b = \begin{cases} 1, if\ product\ is\ collected\ from\ region\ b \\ 0, \quad otherwise \end{cases}$$

x_{itb}: $Number\ of\ from\ product\ i\ collected\ \ from\ region - b, in\ period\ t.$

L_t: $Required\ labor\ source\ in\ period\ t\ (man * hour)$

I_{it}: $Inventory\ of\ product - i\ that\ is\ held\ at\ the\ end\ of\ period\ t.$

$z_1 = Objective - 1$

$z_2 = Objective - 2$

4.3. Parameters

LC_t: $Labor\ cost\ per\ worker\ in\ period\ t$

F_b: $Fixed\ cost\ of\ working\ with\ a\ 3rd\ party\ provider\ to\ collect\ waste\ product\ from\ region\ b.$

T_{im}: $Time\ required\ to\ process\ the\ product\ i\ in\ machine\ m$

G_i: $Manual\ operational\ time\ per\ one\ piece\ of\ product - i.$

$Cap_{m,t}$: $Capacity\ of\ machine\ m\ in\ period\ t\ (hour)$

H_i: $Unit\ Inventory\ Holding\ cost\ of\ one\ piece\ of\ product\ per\ month$

Dis_b: $Distance\ of\ center\ of\ the\ region\ b\ from\ the\ facility$

R_j: $Revenue\ that\ is\ gained\ by\ sales\ of\ material\ j\ per\ kg$

d_{it}: $Amount\ of\ product\ i\ that\ can\ be\ collected\ in\ period\ t$

TC: $Unit\ transportation\ cost\ per\ km\ for\ one\ full - truck\ load.$

Mij: Material j obtained from one piece of product i.

Cm: $Cost\ of\ processing\ for\ one\ machinem\ per\ hour.$

$weight_i$: $Weight\ of\ product\ type\ i\ (kg).$

4.4. Scalars

FTL: $Full\ truck - load\ (kg).$

$Legco$: $Targeted\ collection\ amount\ according\ to\ legislation.$

TC: $Transportation\ cost\ per\ km.$

FCT: $Fixed\ cost\ of\ a\ truck.$

$FiCost$: $Annually\ fixed\ cost\ of\ the\ facility\ (maintanance, office, management..)$

$Legcoweight$: $Weight\ based\ targeted\ collection\ coefficient.$

4.5. Objectives

Objective 1 (Cost minimization)

$$minz = \sum_t L_t LC_t + \sum_{b \in B} F_b * Y_b + \sum_{b \in B} \sum_{t \in T} \sum_{i \in I} \frac{x_{itb}}{FTL} * TC * Dis_b * weight_i + \sum_{b \in B} \sum_{t \in T} \sum_{i \in I} \frac{x_{itb}}{FTL} * weight_i * \mathrm{FCT} + \sum_{b \in B} \sum_{t \in T} \sum_{i \in I} \sum_{m \in M} x_{itb} * T_{im} C_m + \sum_i \sum_t H_i I_{i,t} + - \sum_{j \in J} \sum_i \sum_t \sum_b (R_j) M_{ij} x_{itb} + FiCost \quad (4.1)$$

Objective 2 (Recovery of the most hazardous materials must be maximized)

$$\max z = \sum_{j \in S} \sum_i \sum_t \sum_b x_{itb} * M_{ij} \quad (4.2)$$

4.6. Constraints

Capacity constraint for the machines

$$\sum_i \sum_b x_{itb} * T_{im} \leq Cap_{m,t};\ \forall t, \forall m \quad (4.3)$$

Legislation target constraint

$$\sum_b \sum_t x_{itb} \geq \sum_t d_{it} \times Legco; (\forall i \in I) \quad (4.4)$$

Collection constraint

$$x_{itb} \leq d_{it} * Y_b; (\forall i \in I)\ (\forall b \in B\ )(\forall t \in T\ ) \quad (4.5)$$

Stock balance constraint

$$I_{i(t-1)} + d_{it} - \sum_{b \in B} x_{itb} = I_{it};\ \ (\forall i \in I)\ (\forall t \in T\ ) \quad (4.6)$$

Labor constraints

$$\sum_{i \in I} \sum_{b \in B} x_{itb} G_i = L_t\ ; (\forall t \in T) \quad (4.7)$$

Truck constraints

$$\sum_i weight_i * x_{itb} \leq FTL\ (\forall b \in B)(\forall t \in T) \quad (4.8)$$

Sign constraints:

$$x_{itb} \in Z^+; \quad \forall i \in I;\ \forall t \in T;\ \forall b \in B \quad (4.9)$$

$$L_t \geq 0;\ \forall t \in T \quad (4.10)$$

$$I_{i,t} \geq 0 \forall i \in I; \forall t \in T \quad (4.11)$$

$$Y_b \in \{0,1\};\ \forall b \in B \quad (4.12)$$

In equation 5.1, in the first objective function, total cost is minimized. Labor cost, normal disassembly cost of the collected, products logistics cost (transportation and fixed cost of a truck for every tour), machining cost, total inventory holding cost, annual fixed cost of the facility and disposal cost of hazardous waste are the cost terms considered. Revenue gained from the sales of the recycled materials is subtracted from the sum of the total cost to find the first objective. In the equation 4.2, amount of materials that properly disposed is maximized as second objective. Since not all of the materials are hazardous, only the most dangerous ones are taken into account, this is an environmental objective.

Equation 4.3 satisfies that the required machine hour is no more than capacity of the machines. In equation 4.4 at least target amount of product is recycled that is set by legislations. This target is formulated by product of sales amount and legislative target ratio. Note that, recovery targets are defined in terms of number of products recovered, here. This is called unit-based recovery target. However, alternatively, this constraint is formulated as a weight based target which means at least same tons of WEEE must be recovered. The alternative formulation as the constraint is as follows where Legcoweight shows legislated coefficient for weight-based target [10] :

$$\sum_b \sum_t x_{itb} * weight_i \geq \sum_t d_{it}\ Legcoweight * weight_i;\ (\forall i \in I) \quad (4.13)$$

Equation 4.5 ensures that maximum amount that can be collected from a region is less than the available amount of products in that region. Available amount is equal to electrical-electronic equipment that comes to end-of-life, so the producer can collect them. The amount of recycled product cannot be more than the product that can be collected.

In the stock balance constraint equation 4.6, the inventory of period-t equals to the previous period's inventory plus collection amount at period-t minus the collection amount at period t.

In the equation 4.7 which is a labor constraint shows the work force amount in man-hour.

Truck constraint stipulate that the total collected amount of a region-b in period-t cannot be greater than the full truck load. Equations 4.9, 4.10 and 4.11 are non-negativity and integer constraints, x_{itb} amount of the collected product is integer and L_t and $I_{i,t}$ are greater than or equal to zero. It is shown that Y_b(whether to collect from a region-b) is binary variable in equation (4.12). The legislative weight-based targets are announced in [10].

5. An application for the white goods industry

In this study, the proposed model is implemented to a Reverse Logistics Facility that recovers waste material and safely collects hazardous substances from the refrigerators. In this section, results will be explained after solving the proposed model using GAMS®. In RL, more than one objective may be targeted. The proposed model that is bi-objective, has both economic and environmental concerns. Besides it has a workforce constraint pertaining to the social aspect. Here it is intended to show our model's applicability with a real world data set.

In Figure 1, the costs of different RL stages are shown (transportation and collection, shredding-sorting-dismantling-pretreatment, recycling-recovery, and incineration and landfill) for different product categories, namely cooling& freezing (C&F), lamps, large household appliances (LHHA), small household appliances (SHA), CRT-FDP tubes. Here, the negative values in the bar diagram show the benefit earned out of one unit of this type of product. One can conclude that cooling &freezing products have the greatest benefit potential, if the waste material can be recovered. The reason of selecting the refrigerator in this study is this great benefit potential. In this study there are two types of refrigerators to be recovered: Type-1 is big-size and type-2 is bar-type with a smaller size.

To estimate the amount of waste refrigerator we use production and domestic sales data. The previous years (1992 to 2015) semi-annual production and domestic sales data of refrigerator are available. Since the production and sales amounts are required for the coming years, forecasting method is used. Average lifetime of a refrigerator is accepted as 11 years [38].

The stages of a refrigerator recovery are shown in Figure 2. The first group of stages are manual dismantling, sorting, and separation, and the second one is called mechanical shredding and separation. In yellow rectangles, the waste material that are recovered from the product at each stage are shown.

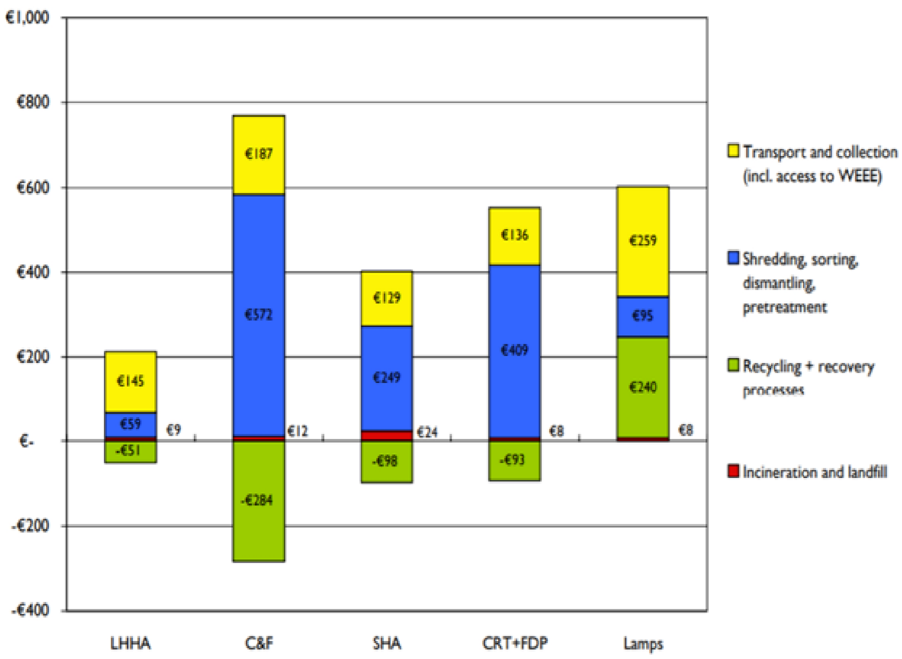

Figure 1. Technical costs for the five main categories in RL per ton in 2007 [37].

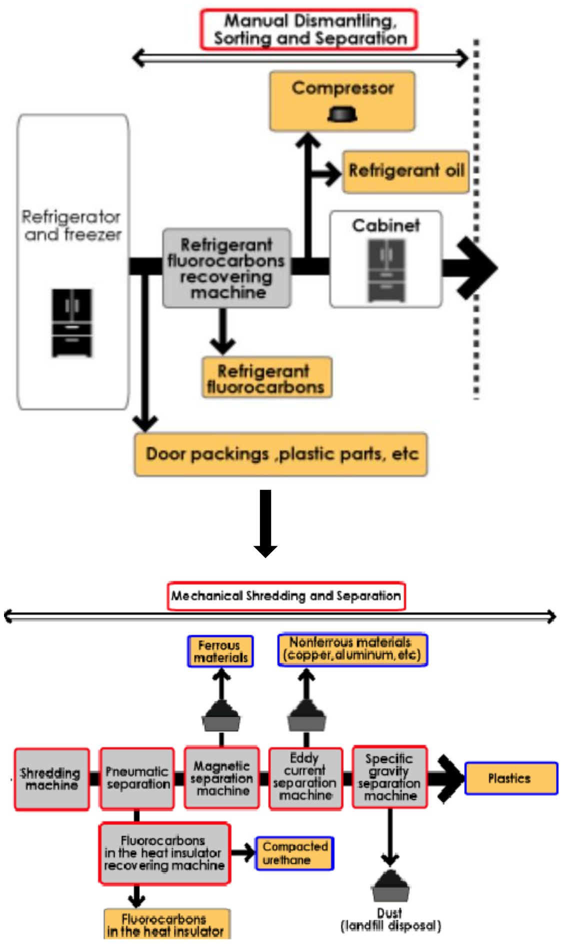

Figure 2. Recovery Stages of the Refrigerators Waste Materials [39].

Table 1. Material composition and scrap value prices for Type-1 and Type-2.

Material	Composition ratio	Disposal cost of hazardous material	Price of scrap material per kg	Revenue obtained for product 1 (30 kg)	Revenue obtained for product 2 (110 kg)
Steel	60%	-	0,5	15.3	56.2
Copper	3%	-	15	16.2	59.5
Aluminum	3%	-	4	2.7	9.9
Polyurethane	10%	-	1.1	3.3	12.1
PVC (cable)	1%	-	5	1.5	5.5
Glass	1%	-	0.4	0.12	0.45
Refrigerant oil	1%	3.5	-	1.05	-3.85
Refrigerant gas	1%	14	-	-4.2	15.4
Plastic	13%	-	1	3.9	14.3
Other	7%	-	0	0	0

Firms make agreements with scrap dealers and second-handlers for scrap metals and parts resulting from the separation of products. According to these agreements, during the return of these products to the market, this company, which carries out RL activities, does not pay an extra fee, contracted firms come and take scrap materials and second hand products.

Harmful materials in the end-of-life products (such as fluorocarbons, urethane) should completely removed from the product and destroyed in such a way not to damage the environment. These activitiees are held in the specialized facilities for a certain price.Our model this price is included in the disposal cost.

Scrap value prices of the materials for the refrigerator recovery are shown in Table 1. Disposal cost values are gathered firm licensed firms and scrap prices are determined based on the current values [40-41].

Distances between the centers of the regions and the WEEE recovery facility located in Eskisehir City are shown in Table 2.

Table 2. Distances from Eskisehir City to the Centers of the Regions(km)

Regions						
(1)	(2)	(3)	(4)	(5)	(6)	(7)
155	340	412	680	975	1030	1116

6. Results and discussion

The model is solved in GAMS® using CoinCbc and Clp Solvers. All computational work is performed in a 64-bit operating system, Intel(R) Core™ i7-6500U 2.50 GHz CPU, and 8.00 GB RAM personnel computer. For the 2017-2018, the aim is to optimize two objective functions. As these functions have a trade-off between each other, when one gets better than the other gets worse. For years between 2014-2018 years data, the model solved with AUGMECON method [42], five different Pareto Optimal Solutions were obtained for each year. Since the first objective function (net cost minimization) is more important than the second one, priority is given to the first objective during the calculations.

In some directives, recovery and recycling targets are given in terms of weight while in some others, targets are given in terms of unit. In WEEE directive that is published by Turkish Government, weight-based targets for companies are defined for every year with increasing rates[10]. However, it has been considered that the revised WEEE target is given in terms of the number of sold products. Therefore, both alternatives are tried separately and compared with each other. Legcoweight stands for target legislation coefficient if weight-based target is given, while Legco is for if uni-based target is given.

Legcoweight and Legco are 0.06 for years 2017 and 2018. The targeted collection amount is calculated as products sold at that period multiplying that legislation coefficients. The payoff table for years 2017 and 2018 is shown in Table 3, according to the weight-based recovery targets. Then, the range of Objective 2 is split into four segments with a length of 11536.75 and five Pareto optimal solutions are obtained for year-2017, as denoted in Table 4. These solutions for 2017 are close alternatives.

Table 3. Payoff table of 2017 and 2018 for weight based target.

		Objective 1	Objective 2
2017	Min Objective-1	1448556	330053
	Max Objective-2	1543446	376200
2018	Min Objective-1	1573116	390644
	Max Objective-2	1801261	501600

For year 2018, the range of Objective 2 is split into four segments with an equal length of 27739, and these five Pareto optimal solutions are also denoted in Table 4. It has been determined that the capacity is insufficient to reach the specified recovery-target of 2018.

Table 4. Trade off table of 2017 and 2018 for weight based target.

	Tradeoffs	Objective 1 (Monetary units)	Objective 2 (kg)	Labor source per month	Total collected WEEE
2017	1	1543446	376200	1500	114000
	2	1519722	364663	1500	109800
	3	1496000	353127	1500	106900
	4	1472272	341590	1500	103510
	5	1448556	330053	1500	100056
2018	1	1801261	501600	2006	152004
	2	1744220	473861	2006	143592
	3	1687183	446122	2006	135143
	4	1630149	418383	2006	126780
	5	1573117	390644	2006	118371

The capacity of bottleneck operations should be increased. To do this, the number of machines 1, 3 and 6 should be increased. All products recycled are Type-1, meaning that it will be sufficient to collect only Type-1 products in zone 1 to achieve the intended collection goal. This decision is made, since the number of products affects both the total cost and the amount of harmful waste recycled. Besides, in terms of workforce requirement, the results show that in year 2017, 1500 hr/month, and in 2018, 2006 hours/month is needed. This increase in workforce requirement is due to the increase in recovery targets.

According to the WEEE directive, 5.5% of the previous year's annual sales must be recovered by a white-goods manufacturer. For year-2018, this target percentage is set as 6%. So, these percentages are multiplied with the annual sales and divided into the twelve to find the monthly unit-based recovery targets. Hence, the recovery targets are found in terms of number of products for 2017 and 2018, and the model is solved, the pay-off is achieved as shown in Table 5.

Table 5. Payoff table of 2017 and 2018 for unit-based target.

		Objective 1	Objective 2
2017	Min Objective 1	946203	119749
	Max Objective 2	959368	130239
2018	Min Objective 1	1002153	123355
	Max Objective 2	1012256	167640

The range of objective 2 is divided into four parts, and five Pareto optimal solutions are achieved as shown in Table 6.

Table 6. Trade off table of 2017 and 2018 for unit-based target.

	Tradeoffs	Objective 1(Monetary units)	Objective 2 (kg)	Labor source per month	Total collected WEEE
2017	1	1292330	130239	832	111391
	2	1230987	127617	832	111392
	3	1198727	124994	832	111392
	4	1139876	122372	832	111990
	5	1082348	119749	832	111990
2018	1	1481091	167640	1045	139280
	2	1397643	156569	1045	137202
	3	1356783	145498	1045	137193
	4	1309845	134426	1169	137121
	5	1264341	123355	1169	137060

For the year-2018, the number of machines of type-1 the bottleneck is increased into two machines. During the 2017, 832 hours/month workforce is required. However, for the year-2018, some results require 1045 and some need 1169 hours/month workforce. The increase in workforce requirement from 2017 to 2018 is similarly due to the increase in recovery targets.

6.1. Comparison of the two target types

If the targets are given in units, products that are more advantageous (bar type fridges) will be preferred in terms of the value gained/unit. Other products may not be preferred because WEEEs are usually collected which are either light in weight or more valuable when recycled. In our model, bar type (Type-2) products are collected firstly if target is given in units. If the target is not reached, Type-1 (bigger size) refrigerators are collected from the regions.

When the weight-based target is given, only the Type-1 product is collected because it is heavier in weight and enough to reach the targets that are set by the legislations.

7. Sensitivity analysis for scrap prices and disposal cost

The sensitivity of total cost of the model to the steel prices is analyzed, both for the unit-based target recovery and for weight based target cases, for years 2018. In Figure 3, X axis shows the change in steel prices, (-20%, -10%, current value, 10%, 20%) and Y axis shows the total cost of the RL model.

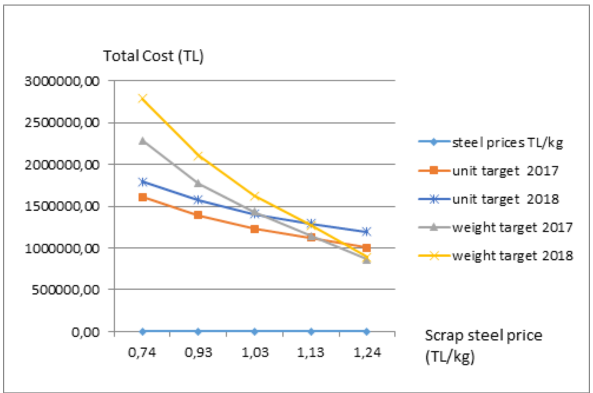

Figure 3. Sensitivity analysis for the scrap steel prices

There is no direct linear relationship between steel metal price and total cost. However, as the steel price increases, the cost decreases to a certain extent. If the target is given in terms of units, the total cost is smaller in all of the scrap values.

The cost decreases with the increase in scrap metal prices. Even though it decreases for both types of targets, if the target is defined on weight based, the reduction will be sharper. If there is a 20% increase in the current scrap metal price, the costs will be close for two target types. Moreover, if the steel price increases by more than 20 percent, total cost of the weight based target case is less than the unit based target case.

The same procedure with α coefficients is applied to copper scrap prices. In the case of the copper price change, the cost of the firm will also decrease as the income from the copper scrap rate increases. The reduction is almost linear. If the copper scrap prices increase by 20%, the costs become equal for the two target types. The results are illustrated in Figure 4.

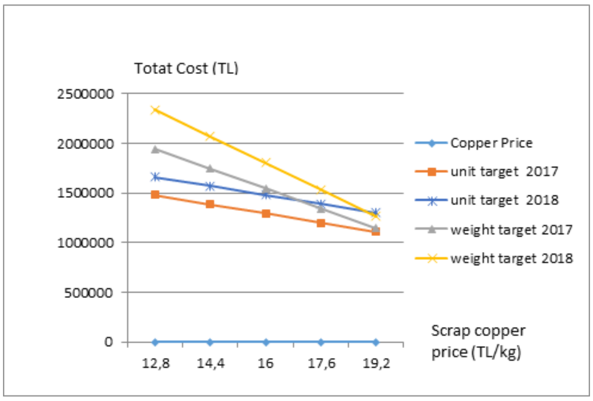

Figure 4. Sensitivity analysis for the scrap prices of copper metal

As seen in the graph in Figure 5, the disposal cost of refrigerant gas is one of the basic units of cost. The 20% reduction in the price of destruction of this harmful chemical can reduce the cost to almost zero. Producers have to send this harmful substance to the licensed company and + 20% change can double the cost. As seen in the analysis, RL activities for firms become much more favorable if the state financially supports the firm with the disposal of these harmful chemicals. Even small support to the firms for the disposal of these wastes can reduce the costs of firms' RL activities and even make them profitable.

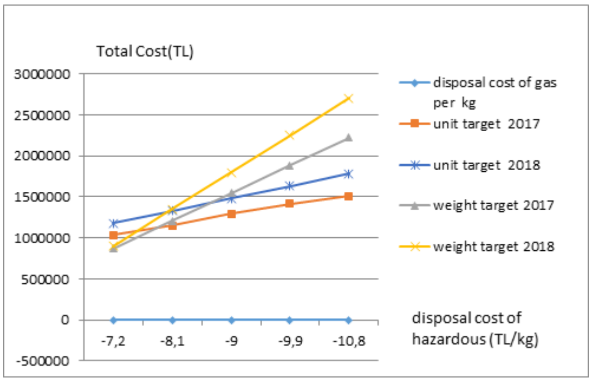

Figure 5. Sensitivity analysis of disposal cost of refrigerant gas.

8. Conclusion

RL is a popular subject, which includes all of the operations related with returned products collection, inspection and recovery to gain value from them. In this study, a bi-objective model is proposed to make an operations planning of an existing reverse logistics facility. In this deterministic MIP mathematical model, cost minimization and maximization of properly disposed hazardous material amount are targeted. The economic objective is accepted as more important where the transportation costs, labor and energy requirements and plant costs are intended to be minimized. Here, the objectives are conflicting, such that one of them become worse while the other one improves. In addition, the real application for operations planning of a real refrigerator recycling facility showed the validity and applicability of the proposed bi-objective model.

In addition, as a novel aspect, the recycling targets are considered in terms of both number of WEE products and weight of the WEEE to be recovered separately, and the model was solved for both of the cases. If the recovery targets are given in terms of number of WEEE products units, the total cost is smaller for the companies. The recycled products are preferred from those that are lighter in weight or easier to carry. Unit-based target model is less affected by the scrap value changes and fuel prices fluctuations. However, recycled materials and properly disposed hazardous materials are comparatively less when this type of target is set by the government.

If targets are given in terms of WEEE weight, firms prefer heavier products. If the value of the scrap increases, a sharper decrease in cost is observed. We can conclude that; it is important to set the target according to the product type.

For every situation, RL incurs an additional cost to the company. The company has not made any profit at all. As the years have passed and the target has increased, there has also been an increase in total cost. In order to prevent this, the state may open its own facilities for the hazardous waste materials recovery. As seen in the sensitivity analysis; the change in disposal cost is causing serious changes in cost. A financial incentive can make RL more attractive to the companies.

In order to increase the number of products collected, incentive may be given per person to give back their used products. However, this is a burden for the companies. If the state imposes a legal sanction to prevent these wastes from being discarded, people will have to deliver these wastes to the competent authorities.

Nature of the reverse supply chain is uncertain. In recent studies, the amount of returned products, costs and scrap prices are considered as uncertain. In our study, a sensitivity analysis conducted for the varying scrap prices and disposal costs of the refrigerant gas. In future studies, stochastic programming can be used as a more advanced technique to model the uncertainty in the RL. Furthermore, if more historical data can be obtained for the returned product quantity and the returned product quality, the model can be installed more accurately and more realistic results can be obtained.

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Emine Nisa Kapukaya *earned her master's degree from Istanbul Technical University, Industrial Engineering Department. She has been working as a research assistant, and continuing her PhD studies at the same department.*

Alperen Bal *earned his master's degree from Istanbul Tehcnical University, Industrial Engineering Department. He has been working as a research assistant in Yalova University, Industrial Engineering Department, and continuing his PhD studies in Istanbul Technical University.*

Sule Itir Satoglu *is a professor of Industrial Engineering, in Istanbul Technical University, Faculty of Management.. Her research interests include sustainable supply chains, lean production systems and humanitarian logistics.*