DESIGNING FUZZY REVERSE SUPPLY CHAIN NETWORK FOR E-WASTE

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Abstract

The reverse supply chain network for e-Waste can be realized with certain operations; e-waste collection, separation, renewal activities, disassembly, recycling and distribution of refurbished products, semi-finished products, raw materials and harmful materials. This study aims to design the reverse supply chain network by considering the responsibility of the producer and the fuzzy parameters that should be dealt complying with the regulation. In order to better reflect the uncertainties in real life in the model, the parameters related to sales prices, product weights, costs, and product demands are assumed to be fuzzy. When the results are examined, the closer the μ value gets to 1, the more strictly the ranges in the equality constraints are controlled. It is also seen that there is a decrease in total gain and total cost.

Keywords: *reverse supply chain network design, e-waste, fuzzy optimization*

1. INTRODUCTION

The processes related to e-waste have recently become a very important research area according to regulations and economic and environmental gains. According to UNEP (2006) annually between twenty and fifty million tons of e-waste are generated around the world and the growth rate of e-waste is about three times higher than other waste types. E-waste is taken into consideration by recycling companies and electronics companies for reasons such as economic gains and parts supply. In addition, the stakeholders such as producers, recycling companies, municipalities, users and waste disposal companies have been responsibilities such as collection, recycling, transportation and disposal of e-waste with the regulations (EU, 2003, 2012). The producers are also responsible to carry out the collection, transport, recycling and disposal costs of e-waste within the framework of the "extended producer responsibility" principle (REC, 2016). Therefore, producers need to redesign reverse supply chain networks to minimize the costs.

The summary of literature on reverse supply chain network design for e-waste is shown in Table 1.

Table 1. Brief Summary of literature on reverse supply chain network design for e-waste (Doan et al., 2019)

Study	Products	Objectives	Model	Uncertain Parameters	Case Study
(Krikke et al., 1999)	Single	C	MILP	-	Copiers
(Srivastava, 2008)	Multiple	P	MILP	-	E-waste
(Achillas et al., 2010)	Multiple	C	MILP	-	E-waste
(Gomes et al., 2011)	Multiple	C	SMILP	Re	E-waste
(Alumur et al., 2012)	Multiple	P	MILP	-	Washing machine and dryers
(Kilic et al., 2015)	Multiple	C	MILP	-	E-waste
(Ayvaz et al., 2015)	Multiple	P	SMILP	Re, Qu, Tc	E-waste
(John et al., 2018)	Multiple	P	MILP	-	Used refrigerators
(Doan et al., 2019)	Multiple	C	FMILP	Re, Qu, Tc, Cc, Dc, Fc, Ic, Rr, Ri, Ca	E-waste
This Study	Multiple	P	FMILP	De, Pc, Bp, Ic, W	E-waste

Note: C: cost minimization, P: profit maximization,'-': not considered, MILP: mixed integer linear programming, SMILP: stochastic mixed integer linear programming, FMILP: fuzzy mixed integer linear programming, De: demand, Re: return quantity, Qu: return quality, Tc: transportation cost, Cc: collection cost, Pc: Processing cost, Dc: disposal cost, Fc: fixed cost, Ic: income, Rr: return rate, Ri: risks, Ca: capacity, Bp: Buying price of return products, W: product weights,

Detailed literature reviews on the reverse and closed-loop supply chain are made by Akçalı et al. (2009), Jayant et al. (2012), Huscroft et al. (2013), Govindan et al. (2015) and Govindan and Soleimani (2017).

When the literature is examined there are a few studies on uncertainties in reverse supply chain network design problems for e-waste. In addition, these studies have considered a limited number of fuzzy parameters. Therefore, fuzzy reverse supply chain network design is a work area that can be improved. This study aims to design the reverse supply chain network by considering the responsibility of the producer and the fuzzy parameters.

This work is structured as follows: the model structure of the fuzzy reverse supply chain network design and an example study are presented in second section. Third section contains results for the sample network. Finally, the last section contains conclusions and future studies.

2. THE MODEL STRUCTURE

2.1. The fuzzy model structure of reverse supply chain network design

In this study, the model presented by Ozgur Polat and Gungor (2019) was tested according to different membership values in order to produce more realistic and effective results by using fuzzy parameters. The mixed integer linear programming model is proposed to maximize total profit of reverse supply chain network according to the responsibility of the producer with fuzzy parameters. Fuzzy parameters are selling prices of fractions, unit buying price of returned products from collection points and stores, disassembly costs, weight of products and demands of fractions in the fuzzy model. The proposed fuzzy model has been solved with an example study by using CPLEX 12.7.1 solver.

The parameter values are calculated by using defuzzification of fuzzy values with membership functions at a certain degree in the fuzzy model. In this study, the ranking fuzzy number through the comparison of its expected intervals approach proposed by Jiménez (1996) and developed by Jiménez et al. (2007),

Parra et al. (2005) and (Pishvaee and Torabi, 2010) is used for defuzzification method accepted in the literature. According to this approach, $\tilde{c}$ is defined a triangular fuzzy number (e^p, e^m, e^o).

The proposed defuzzified mixed integer linear programming model using contains the following assumptions.

- All parameters are known.
- There is no cost associated with management of stores, recovery centers etc.
- Sale prices for each fraction are fixed during the planning period.
- Collection costs of stores and collection points are not considered.
- Manufacturer manages to all processes.
- Capacities of carriers are not considered for transportation
- The recovery rate of all products purchasing from stores is 100% percent.
- All production of hazardous materials is sent to landfills.
- One planning period is considered.
- Demands are divisible.

The equivalent model is as below.

Sets & Indices

$i \in I$	Set of returned product groups
$c \in C$	Set of stores
$t \in T$	Set of carriers
$r \in R$	Set of recovery centers
$k \in K$	Set of collection points
$l \in L$	Set of landfills
$h \in H$	Set of hazardous materials
$u \in U$	Set of fractions (including partial and/or completely disassembled materials)

Parameters

$\tilde{p}_u$	Selling price of fraction u
$\tilde{a}_i$	Weight of product I
$\tilde{g}_i$	Unit buying price of returned product i
$\tilde{gk}_{ik}$	Unit buying price of returned product i from collection point k
w_i^k	On hand amount of product i in collection point k
$\tilde{qd}_{ir}$	Disassembly cost of recovery center r for product i
h_i^t	Unit transportation cost of carrier t for product I
h_h^t	Unit transportation cost of carrier t for hazardous material h

h_u^t Unit transportation cost of carrier *t* for fraction *u*

pu_{iu} Weight percentage of fraction *u* for returned product *i*

ph_{ih} Weight percentage of hazardous materials *h* for returned product *i*

mh_h^l Unit disposal cost of hazardous materials *h*

sl_i^r Productivity rate of recovery center *r* for product *i*

rr_i^k Disassembly rate of collection center *k* for product *i*

y_u^r Disassembly capacity of recovery center *r* for fraction *u*

ca_{ic} Capacity of returned product *i* for store *c*

tcr_c^r Distance between store *c* and recovery center *r*

tkr^{kr} Distance between collection point *k* and recovery center *r*

tlr^{lr} Distance between landfill *l* and recovery center *r*

$d\%_{cu}$ Demand of fraction *u* for store *c*

pr_u^r Minimum disassembly amount of recovery center *r* for fraction *u*

Decision variables

WC_{cu}^{tr} Amount of demand to be fulfilled by stores in store *c* for fraction *u* by using carrier *t* from recovery center *r*

WK_{cu}^{tr} Amount of demand to be fulfilled by collection points in store *c* for fraction *u* by using carrier *t* from recovery center *r*

ZK_i^{tkr} Buying amount of product *i* from collection point *k* to recovery center *r* by using carrier *t*

ZC_i^{tcr} Buying amount of product *i* from store *c* to recovery center *r* by using carrier *t*

XKH_h^{trl} Sending amount of hazardous material *h* for product *i* from collection point *k* to recovery center *r* by using carrier *t* to landfill *l*

XCH_h^{trl} Amount of hazardous material *h* for product *i* from store c to recovery center *r* by using carrier *t* sent to landfill *l*

YR_{cu}^{tr} 1: if store c fraction *u* by using carrier *t* from recovery center *r* uses this path; 0: otherwise.

RU_u Total income related to fraction *u*

CTR_i Logistic cost related to used /end of life product *i (transportation cost)*

CIR_i Total cost related to used /end of life product *i* (*buying cost+disassembly cost*)

CU_u Total cost related to fraction *u (transportation cost)*

CH_h Total cost related to hazardous material *h (disposal cost+transportation cost)*

Objective function:

$$maximize \quad \sum_{u\in U}\left(RU_u - CU_u\right) - \sum_{i\in I}\left(CTR_i + CIR_i\right) - \sum_{h\in H} CH_h \tag{1}$$

Whereas:

$$RU_u = \sum_{c\in C}\sum_{t\in T}\sum_{r\in R}\left(\frac{e_u^p + 2e_u^m + e_u^0}{4}\right)\left(WC_{cu}^{tr} + WK_{cu}^{tr}\right) \qquad \forall u \in U \tag{2}$$

$$CTR_i = \sum_{k\in K}\sum_{t\in T}\sum_{r\in R} h_i^t tkr^{kr} ZK_i^{tkr} + \sum_{c\in C}\sum_{t\in T}\sum_{r\in R} h_i^t tcr^{cr} ZC_i^{tcr} \qquad \forall i \in I \tag{3}$$

$$CIR_i = \sum_{c\in C}\sum_{t\in T}\sum_{r\in R}\left(\frac{gc_i^p + 2gc_i^m + gc_i^0}{4}\right)ZC_i^{tcr} + \sum_{k\in K}\sum_{t\in T}\sum_{r\in R}\left(\frac{gk_{ik}^p + 2gk_{ik}^m + gk_{ik}^0}{4}\right)ZK_i^{tkr} \tag{4}$$

$$+\sum_{c\in C}\sum_{t\in T}\sum_{r\in R}\sum_{k\in K}\left(\frac{qd_{ir}^p + 2qd_{ir}^m + qd_{ir}^0}{4}\right)\left(ZC_i^{tcr} + ZK_i^{tkr}\right) \qquad \forall i \in I$$

$$CU_u = \sum_{t\in T}\sum_{c\in C}\sum_{r\in R} tcr_c^r h_u^t \left(WC_{cu}^{tr} + WK_{cu}^{tr}\right) \qquad \forall u \in U \tag{5}$$

$$CH_h = \sum_{t\in T}\sum_{r\in R}\sum_{l\in L} h_h^t tlr^{lr}\left(XCH_h^{trl} + XKH_h^{trl}\right) + \sum_{t\in T}\sum_{r\in R}\sum_{l\in L} mh_h^l\left(XCH_h^{trl} + XKH_h^{trl}\right) \qquad \forall h \in H \tag{6}$$

s.t.

$$\sum_{t\in T}\sum_{r\in R}\left(WC_{cu}^{tr} + WK_{cu}^{tr}\right) \le \left[(1-\alpha)\frac{dr_{cu}^m + dr_{cu}^0}{2} + \alpha\frac{dr_{cu}^p + dr_{cu}^m}{2}\right] \qquad \forall c \in C, u \in U \tag{7}$$

$$WC_{cu}^{tr} + WK_{cu}^{tr} \ge YR_{cu}^{tr} \qquad \forall t \in T, r \in R, c \in C, u \in U \tag{8}$$

$$WC_{cu}^{tr} + WK_{cu}^{tr} \le M \cdot YR_{cu}^{tr} \qquad \forall t \in T, r \in R, c \in C, u \in U \tag{9}$$

$$\sum_{c\in C}\sum_{t\in T}\left(WC_{cu}^{tr} + WK_{cu}^{tr}\right) \le y_u^r \qquad \forall r \in R, u \in U \tag{10}$$

$$\sum_{t\in T}\sum_{r\in R} ZK_i^{tkr} \le w_i^k \qquad \forall i \in I, k \in K \tag{11}$$

$$\sum_{t\in T}\sum_{r\in R} ZC_i^{tcr} \le ca_{ic} \qquad \forall c \in C, i \in I \tag{12}$$

$$\sum_{c\in C}\sum_{t\in T}\left(WC_{cu}^{tr} + WK_{cu}^{tr}\right) - \sum_{c\in C}\sum_{t\in T} pr_u^r YR_{cu}^{tr} \ge 0 \qquad \forall u \in U, \mathrm{r} \in R \tag{13}$$

$$\sum_{i\in I}\sum_{t\in T} ZC_i^{tcr} sl_i^r \left[(1-\frac{\alpha}{2})\frac{a_i^m + a_i^0}{2} + (\frac{\alpha}{2})\frac{a_i^p + a_i^m}{2}\right] pu_{iu} \ge \sum_{t\in T} WC_{cu}^{tr} \qquad \forall r \in R, c \in C, u \in U$$

$$\sum_{i\in I}\sum_{t\in T} ZC_i^{tcr} sl_i^r \left[(\frac{\alpha}{2})\frac{a_i^m + a_i^0}{2} + (1-\frac{\alpha}{2})\frac{a_i^p + a_i^m}{2}\right] pu_{iu} \le \sum_{t\in T} WC_{cu}^{tr} \qquad \forall r \in R, c \in C, u \in U \tag{14}$$

$$\sum_{i\in I}\sum_{t\in T}\sum_{c\in C} ZC_i^{tcr} sl_i^r \left[(1-\frac{\alpha}{2})\frac{a_i^m + a_i^0}{2} + (\frac{\alpha}{2})\frac{a_i^p + a_i^m}{2} \right] ph_{ih} \geq \sum_{t\in T}\sum_{l\in L} XCH_h^{trl} \quad \forall r \in R, h \in H$$

$$\sum_{i\in I}\sum_{t\in T}\sum_{c\in C} ZC_i^{tcr} sl_i^r \left[(\frac{\alpha}{2})\frac{a_i^m + a_i^0}{2} + (1-\frac{\alpha}{2})\frac{a_i^p + a_i^m}{2} \right] ph_{ih} \leq \sum_{t\in T}\sum_{l\in L} XCH_h^{trl} \quad \forall r \in R, h \in H \tag{15}$$

$$\sum_{i\in I}\sum_{t\in T}\sum_{k\in K} ZK_i^{tkr} rr_i^k sl_i^r \left[(1-\frac{\alpha}{2})\frac{a_i^m + a_i^0}{2} + (\frac{\alpha}{2})\frac{a_i^p + a_i^m}{2} \right] pu_{iu} \geq \sum_{t\in T} WK_{cu}^{tr} \quad \forall r \in R, c \in C, u \in U$$

$$\sum_{i\in I}\sum_{t\in T}\sum_{k\in K} ZK_i^{tkr} rr_i^k sl_i^r \left[(\frac{\alpha}{2})\frac{a_i^m + a_i^0}{2} + (1-\frac{\alpha}{2})\frac{a_i^p + a_i^m}{2} \right] pu_{iu} \leq \sum_{t\in T} WK_{cu}^{tr} \quad \forall r \in R, c \in C, u \in U \tag{16}$$

$$\sum_{i\in I}\sum_{t\in T}\sum_{k\in K} ZK_i^{tkr} rr_i^k sl_i^r \left[(1-\frac{\alpha}{2})\frac{a_i^m + a_i^0}{2} + (\frac{\alpha}{2})\frac{a_i^p + a_i^m}{2} \right] ph_{ih} \geq \sum_{t\in T}\sum_{l\in L} XKH_h^{trl} \quad \forall r \in R, h \in H$$

$$\sum_{i\in I}\sum_{t\in T}\sum_{k\in K} ZK_i^{tkr} rr_i^k sl_i^r \left[(\frac{\alpha}{2})\frac{a_i^m + a_i^0}{2} + (1-\frac{\alpha}{2})\frac{a_i^p + a_i^m}{2} \right] ph_{ih} \leq \sum_{t\in T}\sum_{l\in L} XKH_h^{trl} \quad \forall r \in R, h \in H \tag{17}$$

$$WC_{cu}^{tr}, WK_{cu}^{tr}, ZK_i^{tkr}, ZC_i^{tcr}, XKH_h^{trl}, XCH_h^{trl} \geq 0 \quad YR_{cu}^{tr} \in [0,1]$$
$$\forall c \in C, i \in I, k \in K, t \in T, r \in R, u \in U, h \in H, l \in L \tag{18}$$

Objective function determines the maximization of the profit for the reverse supply chain network. It contains selling revenue of fractions and cost of buying, disassembly and disposal. Model constraints define disassembly/transportation/depot capacity, demand fulfillment, the product balance, conversion values of fractions and hazardous materials, minimum recovery limit and structure of variables.

2.2. An example study

The sample network has four stores demanding eight different fractions disassembled from three types of products. The network contains three carriers, two landfills, three collection points and three recovery centers. One hazardous material is sent to the landfills. Figure 1 shows the example study of the reverse supply chain network.

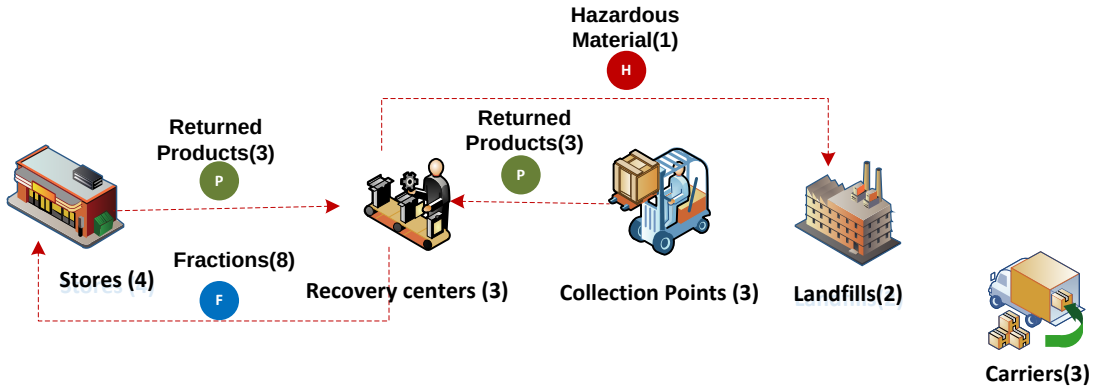


Fig. 1. The example study of reverse supply chain network

Some of the specific variables and fuzzy parameters used in the example study are shown between Table 2-5.

Table 2. Buying prices and weights of returned products

i	$g\tilde{c}_i$	$\tilde{a}_i$
1	[0.3, 0.4, 0.5]	[8.0, 9.71, 10]
2	[0.1, 0.25, 0.45]	[4.0, 4.62, 5.0]
3	[0.1, 0.2, 0.3]	[6.2, 7.24, 7.8]

Table 3. Unit buying price of returned products from collection points

	i	$k1$	$k2$	$k3$
$g\tilde{k}_{ik}$	1	[0.1, 0.15, 0.2]	[0.09, 0.1, 0.12]	[0.08, 0.09, 0.1]
	2	[0.1, 0.12, 0.15]	[0.07, 0.08, 0.09]	[0.06, 0.07, 0.1]
	3	[0.04, 0.05, 0.07]	[0.03, 0.04, 0.05]	[0.02, 0.04, 0.06]

Table 4. Disassembly costs of recovery centers

	i	$r1$	$r2$	$r3$
$q\tilde{d}_{ir}$	1	[0.007, 0.009, 0.01]	[0.01, 0.012, 0.02]	[0.02, 0.024, 0.04]
	2	[0.008, 0.009, 0.01]	[0.01, 0.015, 0.02]	[0.006, 0.008, 0.01]
	3	[0.006, 0.007, 0.008]	[0.007, 0.008, 0.009]	[0.008, 0.009, 0.01]

Table 5. Selling prices and demands according to fractions

u	$\tilde{e}_u$	$d\tilde{r}_{c1u}$	$d\tilde{r}_{c2u}$	$d\tilde{r}_{c3u}$	$d\tilde{r}_{c4u}$
1	[0.7, 0.85, 1.05]	[150. 200. 250]	[100. 120. 160]	[300. 310. 320]	[200. 230. 260]
2	[0.6, 0.7, 0.9]	[260. 280. 300]	[200. 240. 260]	[100. 110. 140]	[100. 120. 140]
3	[0.3, 0.5, 0.6]	[100. 110. 120]	[180. 200. 220]	[300. 320. 340]	[200. 210. 220]
4	[0.1, 0.3, 0.4]	[300. 320. 340]	[200. 240. 260]	[100. 150. 160]	[310. 320. 330]
5	[0.2, 0.4, 0.6]	[200. 210. 220]	[100. 160. 200]	[300. 310. 320]	[60. 70. 80]
6	[0.15, 0.3, 0.45]	[200. 220. 240]	[300. 310. 320]	[200. 240. 260]	[120. 150. 160]
7	[0.1, 0.2, 0.3]	[60. 65. 70]	[390. 400. 410]	[100. 110. 120]	[220. 240. 260]
8	[0.05, 0.1, 0.3]	[150. 200. 210]	[90. 100. 110]	[40. 50. 60]	[300. 330. 360]

3. RESULTS

The proposed model contains 1119 variables and 63311 constraints. All experiments were performed on a workstation with Intel Core i7, 3.4 GHz processor and 8 GB of RAM. Table 6 shows the monetary results according to different membership values between 0 and 1, where $\mu = 0$ reflects unrealistic, $\mu = 0.5$ reflects with 50% probability and $\mu = 1$ reflects completely realistic solutions.

Table 6. Monetary results according to μ values (x1000)

	μ = 0	μ = 0.5	μ = 1
Total Profit	557.29	536.33	515.41
Total Gain	876.39	852.18	824.66
RU_u	876.39	852.18	824.66
Total Cost	319.10	315.85	309.25
CTR_i	55.10	55.28	54.65
CIR_i	105.91	106.49	105.43
CU_u	157.91	153.89	148.96
CH_h	0.18	0.19	0.20
CPU Time (sec.)	3.86	2.59	28.16

When the Table 6 is examined, transportation costs of fractions are the highest value in the total cost. The total profit and total cost are decreased the closer the μ value gets to 1. The reason for this is the tightness in equality constraints according to weights. It is seen that there is a 7.52% decrease in total gain and %3.09 decrease in total cost of μ = 1 compared to μ = 0 value. 36.89% of total demand was met for μ = 1 value. In addition, 52.31% of this demand was met from the collection center and 47.69% was met from the stores.

4. CONCLUSIONS

In this study, reverse supply chain network design is developed by considering the responsibility of the producer and the fuzzy parameters. The proposed fuzzy mixed integer linear programming model is compared for an example study according to different membership values. As a result of this study, it is tried to guide the producers about which data should be considered as fuzzy and how to manage the reverse network more effectively.

In the future, the problem will be solved with real data. In addition, metaheuristic approaches will be developed to solve large scale problem sets.

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