Using Compromised Method in Design of Reverse Logistics Network With Eco-Efficiency Consideration

M. Fathi [1], A. Hasanzadeh[2], F. Dehghanian [2], S. Mansour [2]
[1] Department of Industrial Engineering, Iran University of Science and Technology, Tehran, Iran
[2] Department of Industrial Engineering, AmirKabir University of Technology, Tehran, Iran
(mfathi@iust.ac.ir)

Abstract - **Increasing importance of sustainable development has lead eco-efficiency to find a specific position in literature. Eco-efficiency means producing goods and delivering services by using lower energy and raw material which together result in lower amount of wastes, pollution and cost. Eco-efficiency considers two aspects: economical and environmental. The purpose of this article is to design reverse logistics network whose eco-efficiency satisfies the opinion of decision maker. So a bi-objective linear programming model (minimizing cost and environmental effects) is developed and efficient points of model are found. In the following, using interactive method of STEM that considers trade-offs between economic and environmental objectives in interaction to decision maker, an efficient recovery network is presented.**

Keywords - **Supply chain network design, Sustainable supply chain, Sustainable development, Eco-efficiency, Compromised methods, STEM.**

I. INTRODUCTION

One of the most intensively discussed concepts in the international political debate today is the concept of sustainability. According to Bertland report, sustainability means that current generations should meet their needs without future generations to meet their own needs deal with shortage and difficulty [10]. Sustainable development is a complicated concept that includes variant aspects.

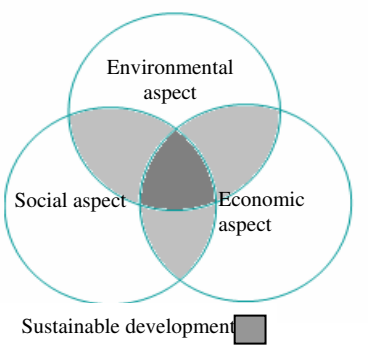

Fig. 1. Sustainable development aspects [1]

In sustainability, economic, social and environmental aspects are closely tied to each other and researchers almost study sustainability in triple bottom line of economic, social and environmental aspects. In sustainable development, objectives should consider triple aspects simultaneously as following:

- Provide social development that needs of all people are met in it.
- Protect environment efficiently and consume natural resources carefully.
- Result sustainable economic development.

It goes without saying that developed countries have passed the basis stages of development in era of history although those countries used the most sources and utilization from natural resources, they have imposed the most damages and haven't paid any repayments. This occurrence happened considerably from industrial revolution until twentieth century. But today continuance of this trend is very dangerous and almost infeasible, so environmental problems and attention to sustainable development bodily has converted to a universal slogan and motion. Universal society and especially developed countries have paid attention to environment and have announced that environmental costs must be considered in all production process [1].

Eco-efficiency considers two aspects: economical and environmental. Eco-efficiency means producing goods and delivering services by using lower energy and raw material which together result in lower amount of wastes, pollution and cost. Eco-efficiency is globalized after that Schmidheiny introduced it in Changing Course book in 1992. (This book is presented in UNCED conference and was about sustainable development and environmental problems.) This book almost mentioned as origin of eco-efficiency concept. In this book Schmidheiny essentially has focused on natural capacity for absorbing wastes, reducing radiances and economic growth as well. World Business Council for Sustainable Development (WBCSD) has the important role for knowing this concept in industry and different information and case studies of eco-efficiency give to industry from various ways such as website [11].

Many discussions related to requirements and models of life have started for sustainable development. But these discussions are in the initial steps. Today we observe many reactions to environmental pollution in national levels. Governments have provided regulations whether national and international for considering environmental problems . For instance, we can imply Kyoto agreement for green house gasses reduction in order to prevent ground over warming. Today Europe Union the most advocate of sustainable development. Europe Perelman

knows sustainable development for Europe future very vital and in initiative steps has legalized regulations for electronic parts wastes [1]. In Iran, waste management regulation was also approved in order to determine waste management circumstance related to agricultural and production areas in the year 2004. This paper tries to study paper recovery network design regarding to economic and environmental factors simultaneously. Whereas eco-efficiency analysis studied two aspect of economical and environmental, this paper virtually follows a network that is efficient regarding to environmental.

II. Literature review

Eco-efficiency literature in network design area is limited to just two papers. Firstly, Frota Neto et al. [4] developed a framework in order to design and evaluate sustainable logistics networks based on Data Envelopment Analysis (DEA) and presented a multi-objective linear programming. Finally, in order to evaluate presented model, it was implemented for paper and paste industry. In the proposed bi-objective model of this paper, minimization of cost and environmental effects are considered as two objectives of logistics network design.

Frota Neto et al. [5] presented a method for eco-efficiency evaluation in logistics networks named Eco-topology. Assemblage of electronic parts wastes in Germany was considered as a case study to implement Eco-topology method. The model of case study was presented as a three-objective model. The objective functions of this model were to maximize profit and to minimize wastes and energy demands. Given an objective function as constant, they found efficient points of model to other two objectives. This approach helps us that three objectives trade-offs are evaluated quantitatively.

The advantage of two papers as mention above to previous research in eco-efficiency field is that an efficient method with capability of trade-offs between economic and environmental objectives is presented. The weak point of presented models in these papers is that they don't interact with decision maker opinions through decision making process. This paper tries to study paper recovery network design to use articulated methods with considering economic and environmental problem. Articulated methods interact with decision makers and consider their opinions in the model to achieve decision maker's desired solution. Hence, we apply STEM method for this purpose.

III. The STEM method

STEM was introduced by Benayoun et al. [6] in 1971. This method is used for solving a multi-objective model. Also this method allows the decision-maker to "learn" to recognize good solutions and the relative importance of the objectives as following steps:

Step 0- Construction of pay-off matrix**:** This matrix is constructed before the first cycle. For this, optimal solution (f_j^*) of each objective function obtained by solving the following mathematical model:

$$\begin{aligned} &Max: Z_j = f_j(x) = C_j^t x \quad ; j = 1,2,...,k \\ &s.t.\ \ Ax \le b \\ &\quad x \ge 0 \end{aligned}$$

Regarding to optimums resulted in previous step, we construct Pay-off matrix whose row *j* corresponds to the solution optimizing the objective function *j* and each of Z_{ij} is the value taken on by the objective function *i* when objective *j* reaches its ideal (f_j^*).

Step 1- Calculation stage: Following linear mathematical programming solved in cycle *M* which γ is the "nearest", in the MINIMAX sense, from the optimum solution (f_j^*):

$$\begin{aligned} &Min\ \gamma \\ &s.t.\ \ \gamma \ge (f_j^* - f_j(x)).\beta_j \quad : j = 1,2,...,k \\ &x \in S^m \\ &\gamma \ge 0 \end{aligned}$$

S^m includes the constraints $\begin{cases} Ax \le b \\ x \ge 0 \end{cases}$ beside constraints that is added to problem in previous cycle *m-1*.

The coefficients β_j give the relative importance of the distances to the optima, but it must be noted that they are only locally efficient and are not of overriding importance as the weights are in the Utility method. If $f_j^{\min}$ is the minimum value of column *j* in the pay-off matrix; we choose β_j such that

$$\beta_j = \frac{\alpha_j}{\sum_{i=1}^{k} \alpha_i}$$

$$\alpha_j = \begin{cases} \dfrac{f_j^* - f_j^{\min}}{f_j^*}\left[\dfrac{1}{\sqrt{\sum_{i=1}^{n}(C_{ij})^2}}\right] & f_j^* > 0 \\ \dfrac{f_j^{\min} - f_j^*}{f_j^*}\left[\dfrac{1}{\sqrt{\sum_{i=1}^{n}(C_{ij})^2}}\right] & f_j^* < 0 \end{cases}$$

C_{ji} Shows the coefficient of objective *j* for available variable and α_j Obtains from multiplying two terms. From term 1, we infer that the value of f_j does not vary much from the optimum solution for varying X, the corresponding objective is not sensitive to a variation in the weighting values; so a small weight β_j can be assigned to this objective function. But the term 2 normalizes the values taken by the objective functions.

Additionally β_j is that $\sum \beta_j = 1$, so different solutions obtained from different weighting strategies can be easily compared.

Step 2- Decision phase: The compromise solution (F^m resulted in x^m) and obtained from phase 1 is proposed to the decision-maker. Decision maker recognizes that some of f_j^m rather than their ideal values (f_j^*) *are* satisfactory and finally must accept a certain amount of relaxation of a satisfactory objective (Δf_j) to allow an improvement of the unsatisfactory ones in the next cycle. Hence for the next cycle the feasible region is modified following as:

$$S^{m+1} = \begin{cases} S^m \\ f_j(x) \geq f_j(x^m) - \Delta f_j \\ f_l(x) \geq f_l(x^m) \; ; l \neq j ; l = 1,2,...,k \end{cases}$$

Coefficient β_j for *j*th objective function in order to solve the cycle m+1 equal to zero and repeat the solving of existing problem from step 1 for m+1 cycle and S^{m+1}.

Step 3- step 1 and 2 are repeated until the all values of f_j^m were satisfied by decision makers.

IV. Paper recovery network design

We want to design a paper recovery network in Tehran metropolis. In this case, a warehouse of collecting paper wastes has been spotted for each zone of Tehran city and the amount of paper wastes have been determined annually. A set of candidate points are spotted for establishing paper recovery plants. The Question is which candidate points are suitable to establish plants and from which zone (warehouse of collecting paper wastes) paper can be supplied for them. Each plant could have three kinds of process for recovery that has variant environmental effects. Paper recovery network design was modeled with two objectives (Economic and Environmental):

1-Economic: minimization of costs included transportation costs and setup and performance cost plant.
2-Environmental: minimization of environmental effects included transportation and production processes effects.

A. *Mathematical model*

The following variables and indices are used in the mathematical model definition.

- Indices and Sets

Set of candidate site for warehouses for collecting paper	$i \in I$	$I = \{1,2,...,i\}$
Set of candidate site for plants	$j \in J$	$J = \{1,2,..., j\}$
Set of Production Method	$k \in K$	$K = \{1,2,...,k\}$

- Model Parameters

Parameter's notation	Description
f_{jk}	*Fixed cost of opening a warehouse at site j*
c_{ij}	*Fixed cost of opening a warehouse at site j(for providing product k)*
ec_{ij}	*Demand of customer k for product i*
cp_{jk}	*Cost of Supplying* d_{ik} *for customer i (for product k) delivered from warehouse at site j*
ecp_{jk}	*Environmental effects of k th producing method in plant j*
V_i	*Capacity of warehouse at site i*
V_j'	*Capacity of plant at site j*
m	*Number of plants to open.*

- Decision Variables

Variable	Description
z_j	*Fraction of demand of customer i for product k delivered from warehouse at site j*
y_{jk}	*1 if warehouse j supply product i, otherwise 0.*
x_{ij}	*1 if warehouse j open at site j, otherwise 0.*

- Mathematical Formulation

The model for multi-objective programming is represented as follows:

$$Min\, Z_1 = \sum_{j\in J}\sum_{k\in K} f_{jk}.y_{jk} + \sum_{i\in I}\sum_{j\in J} c_{ij}.x_{ij} + \sum_{i\in I}\sum_{j\in J}\sum_{k\in K} cp_{jk}.x_{ij} \quad (1)$$

$$Min\, Z_2 = \sum_{i\in I}\sum_{j\in J} ec_{ij}.x_{ij} + \sum_{i\in I}\sum_{j\in J}\sum_{k\in K} ecp_{jk}.x_{ij} \quad (2)$$

s.t.

$$x_{ij} \leq z_j.V_j' \quad \forall i, j \quad (3)$$

$$\sum_{k\in K} y_{jk} = z_j \quad \forall j \quad (4)$$

$$\sum_{j\in J} x_{ij} = V_i \quad \forall i \quad (5)$$

$$\sum_{i \in I} x_{ij} = V'_j \quad \forall j \tag{6}$$

$$\sum_{j \in J} z_j = m \tag{7}$$

$$x_{ij} \geq 0 \tag{8}$$

$$z_j \in \{0,1\} \tag{9}$$

$$y_{jk} \in \{0,1\} \tag{10}$$

Objective function (1) is related to economic objective function that follows minimization of annual setup and production processes costs of plants and as well as transportation cost between warehouse to plants. Objective function (2) follows minimization environmental effects result of transportation between warehouse to plant and production processes of plants. Constraint (3) emphasizes this subject that just if paper is dispatched to plant *j* that were established (up to capacity maximum). Constraint (4) implies each plant must to have one production process. Constraint (5) is related to output capacity constraint of warehouses. Constraints (6) and (7) respectively capacity and number of plants Constraint are shown. Constraint (8), (9) and (10) are also related to Constraint of sign and kind of used variables in model.

B. Paper recovery network design in Tehran

Indices and Sets were introduced as follow:

- In each 22 zone a warehouse for collecting paper is considered.
- For establishing plants in each zone, a candidate site is considered: $j \in J, J = \{1,2,3,...,22\}$
- According to Bloemhof-Ruwaard et al. [7] ,there are 4 main Technology for paper recovery:
    1. Bleach sulphate
    2. Unbleached sulphate
    3. Bleached sulphite
    4. Bleached thermo-mechanical pulp

Capacity of warehouse estimation (V_i)

Here, collected garbage amount in June of 2008 is given as monthly capacity average of warehouse in each zone. Hereby for calculating annual capacity of zones warehouses, carton and paper wastes amount of June multiply in number 12 and warehouse capacity of 22-zone is obtained as table 1:

Table 1
Capacity of warehouse in zones

Zones	Collected paper and carton per month(kg)	Collected paper and carton per year(kg)
1	66322	795864
2	1365072	16380864
3	169571	2034852
4	569266	6831192
5	329666	3955992
6	679425	8153100
7	257138	3085656
8	456386	5476632
9	171715	2060580
10	48164	577968
11	643120	7717440
12	528511	6342132
13	222430	2669160
14	353851	4246212
15	170801	2049612
16	285780	3429360
17	45492	545904
18	87871	1054452
19	19437	233244
20	144110	1729320
21	54030	648360
22	99040	1188480

Capacity of established Plant (V'_j)

22 zones are assumed as a set of candidate sites for establishing plant. Three kinds of capacity are considered for candidate sites of establishing plant. Tehran is divided to 3 parts and in order to supply demand of warehouses paper wastes, average capacity is evaluated based on information of the above table in June of 2008.

Plants annual cost (f_{jk})

To obtain information related to setup and operations cost of recovery plants with different technology, view points of Salehabad Paper Recovery Company's accounting unit was used. It's obvious that these costs almost are estimative.

Eco-efficiency effects calculation

In this model, environmental objective function included environmental effect of paper production method in plants and environmental effect resulted in transportation between warehouse and plants are considered. To calculate these effects, available environmental information of paper and paste industry of Europe is used [1].

This paper considers environmental problems of Global warming, Human Toxicity, Ecotoxicity, Photo-Chemical Oxidation, Acidification, Nitrification and Solid waste as environmental effects. Environmental effects for four methods of paper production and transportation (per ton product) were calculated and normalized for each of above indexes in paper and paste industry of Europe and (see table 2).

Table 2
Normalized indexes of environmental effects

Process	Global warming	Human Toxicity	Ecotoxicity	Photo-Chemical Oxidation	Acidification	Nitrification	Solid waste
Production Method1	16	42	79	35	53	31	81
Production Method1	7	33	32	31	36	17	52
Production Method1	56	100	100	100	100	100	80
Production Method1	100	43	52	35	58	13	92
Transportation	0.004	0.002	0	0.001	0.003	0	0

To calculate environmental effects of paper production and transportation methods (ecp_{ij}), environmental effects average in different categories was used. Indeed average numbers of each row in table 2 implies environmental effect of respective production method.

C. Solving the model using articulated method

In this section, paper recovery network design model is solved using STEM method and considering a given decision maker (like municipality in charge of recovery and collecting). Mathematical model of paper recovery network design case study is coded with Lingo 8 optimization software. Steps of STEM are as follow:

First cycle

Step 0- Construction Pay-off matrix**.** Pay-off matrix for paper recovery network design is shown in table 3.

Table 3
Pay-off matrix

	Z_1	Z_2
Z_1	15203280	20860530
Z_2	28083040	19068700

Step 1- Calculation Phase

In this phase, values of α_1, α_2 are calculated for two economic and environmental objective functions and then values of β_1, β_2 are calculated from α_1, α_2 **.**

$$\alpha_1 = \frac{f_1^{\min} - f_1^*}{f_1^*}\left[\frac{1}{\sqrt{\sum_{i=1}^{n}(C_{1j})^2}}\right] = 0.5 \; ; \alpha_2 = \frac{f_2^{\min} - f_2^*}{f_2^*}\left[\frac{1}{\sqrt{\sum_{i=1}^{n}(C_{2j})^2}}\right] = 0.5$$

$$\beta_1 = \frac{\alpha_1}{\alpha_1 + \alpha_2} = 0.5 \; ; \beta_2 = \frac{\alpha_2}{\alpha_1 + \alpha_2} = 0.5$$

Then, we should solve following linear programming:

$$\begin{aligned} &\min : \gamma \\ &s.t. \;\; \gamma \geq (15203280 - f_1(x)).(0.5) \\ &\quad \gamma \geq (19068700 - f_2(x)).(0.5) \\ &\quad x \in S^m \\ &\quad \gamma \geq 0 \end{aligned}$$

Optimal solution result in this model becomes following:

Step 2- Decision Making**.** Solutions resulted in previous stage are report to decision maker and decision maker compares objective function with amounts (15203280, 19068700) that are calculated in productivity matrix.

$$F^* = (f_1^*, f_2^*) = (15203280, 19068700)$$

$$F^1 = (f_1^1, f_2^1) = (21159040, 19250630)$$

Economic costs of paper recovery design (f_1^1) are satisfactory for decision maker but environmental effects of paper recovery design (f_2^1) are not satisfactory and decision maker is also interested in relaxation $\Delta f_1 = 200$ from economic costs of paper recovery network (f_1^1) for improvement in environmental effects of paper recovery design (f_2^1). Hence, new feasible region for second cycle of STEM are as following:

$$S^2 = \begin{cases} S^1 \\ f_1(x) \leq f_1(x^1) + \Delta f_1 \\ f_2(x) \leq f_2(x^1) \end{cases}$$

$$\Rightarrow S^2 = \begin{cases} S^1 \\ f_1(x) \leq 21159040 + \Delta f_1 \\ f_2(x) \leq 19250630 \end{cases}$$

Then, we attain to second cycle of STEM method and continue stages again.

Second cycle

*Step 1- N*ew values of β_1, β_2 are: $\beta_1 = 0, \beta_2 = 1$

We should solve the problem of second cycle:

$$\min : \gamma$$
$$s.t.\ \ \gamma \geq 19068700 - f_2(x)$$
$$x \in S^2$$
$$\gamma \geq 0$$

By solving this model, software dose not obtain to feasible solution in second cycle and so the problem is infeasible. Decision maker with STEM method consents to paper recovery network design with economic costs 21159040 and environmental effects 19250630.

Proposed Network of STEM Method

Fig. 2. Shows recovery network design of this decision maker that are established plants in zones 5, 8 and 12 and paper supply flow and dispatched paper amount are according to Fig. 2. Amount of network economic costs is 21159040 and amount of network environmental cost is 19250630.

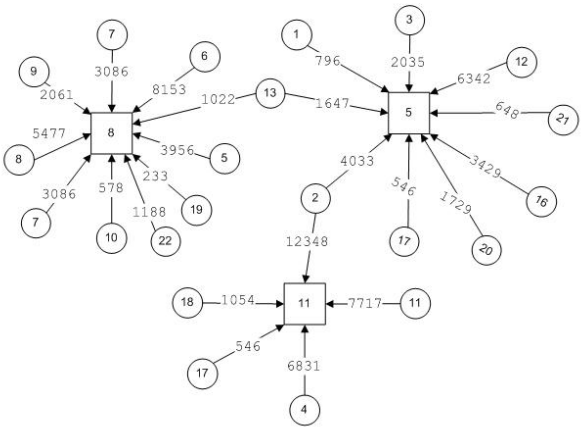

Fig. 2. Recovery network result in STEM method

V. Comparison of STEM method and unarticulated methods

For evaluating advantage of this method, we compare this method with several unarticulated methods presented in literature. Unarticulated methods mainly find efficient solutions and then try to improve actual situation in according to efficient solutions set. Fig. 3. Shows this situation. In Efficient frontier network design (Pareto) obtain according to economic and environmental objective functions. In the following, we should present an approach for actual situation that gets efficient frontier.

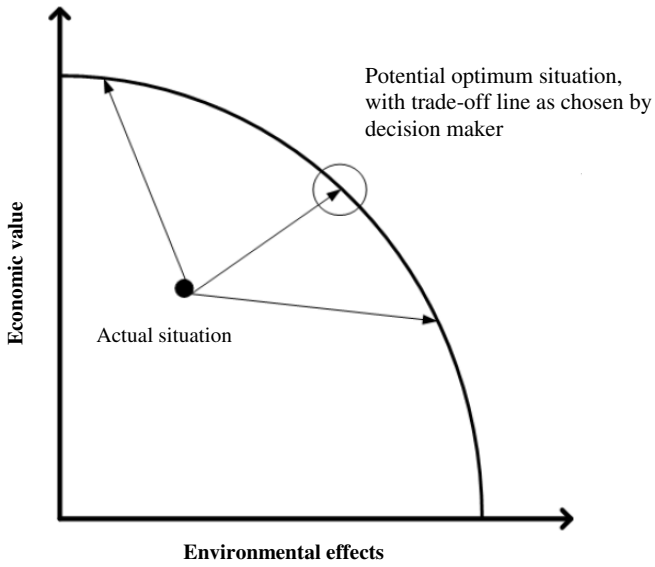

Fig. 3. Eco-efficiency improvement in Logistics Network

According to literature, Radial Projection and nonlinear programming model are methods that can be used obtaining efficient frontier. In Radial Projection method, we draw a line from zero coordinate to actual situation and contact spot of this line with efficient frontier is a point that we must shift to it to reach efficiency [1].

Frota Neto et al. [4] presented a nonlinear programming model for picturing actual situation that concept of the model is to find minimum of needed distance for picturing inefficient actual situation on efficient frontier. This model leads actual situation to efficient frontier from the nearest path (i.e. at least increase in economic value and environmental indexes). If we consider (a,b) as inefficient actual situation coordinate (a coordinate on horizontal pivot of environmental objective function and b coordinate on vertical pivot of economic objective function) and (a^j, b^j) as points coordinate on Pareto frontier and δ_1 is maximum horizontal distance of inefficient point of environmental coordinate (a) to pareto frontier (a^j) and δ_2 is maximum vertical distance of inefficient point of economic coordinate (b) to pareto frontier (b^j), mathematic model implies as following:

$$Min \sqrt{\delta_1^2 + \delta_2^2}$$
$$s.t.\ a - \delta_1 - a^j < 0$$
$$b - \delta_2 - b^j < 0; \forall (a^j, b^j) \in ND$$

To implement the above mentioned methods in a case study, using constraint method, efficient points for paper recovery network design are represented in table 4 and Fig. 4.

Table 4
Efficient points for paper recovery network

Point	Economic objective function(Z_1)	Environmental objective function(Z_2)
1	15203280	20860530
2	15203280	20661438
3	15203300	20462346
4	15203340	20263253
5	15203390	20064161
6	15457760	19865069
7	15630900	19665977
8	16637210	19466884
9	21613130	19267792
10	28083040	19068700

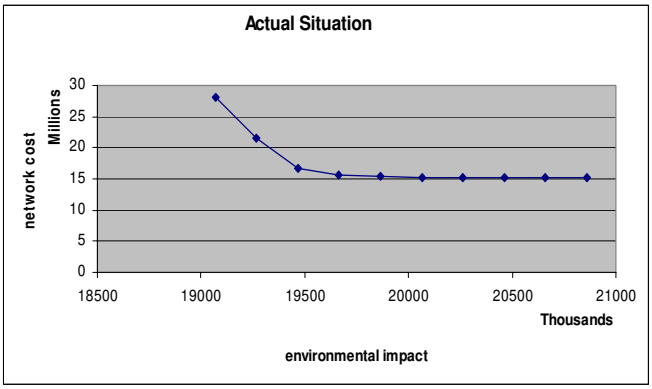

Fig. 4. Efficient points for paper recovery network

Actual Situation Improvement

There are two paper recovery plants in zones 18 and 20 of Tehran that their production capacities are respectively 224 and 100 ton in year and Altogether 324 ton carton produce. Current plants capacity is not sufficient for paper waste recovery in zones warehouses and this subject causes that amount of collected paper wastes are burnt or are graved that regarding to economic are not commodious. Due to this amount of paper wastes have never been considered in current paper recovery network design of Tehran environmental discussions and this is cause on design improvement importance of this network. Economic costs of Actual paper recovery network are 20625130 and environmental cost is 20752352.

In Radial Projection method, we should draw a line from zero coordinate to actual situation and conflict spot of this line with efficient frontier is the point that one must shift to it to reach the upper efficiency. Suggestion of Radial Projection method results in a point with economic objective function 15203351 and environmental costs 20263248.

Proposed Network of Radial Projection Method

Plants are established in zones 5, 8 and 12 and paper supply flow and dispatched paper amount from warehouses to plants are shown in fig. 5. Amount of network economic costs is 15203351 and amount of network environmental costs is 20263248.

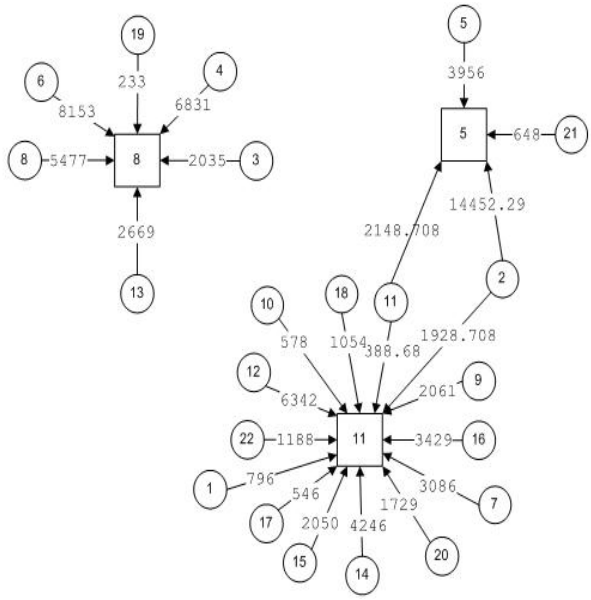

Fig. 5. Recovery network result in Radial Projection method

In Nonlinear Programming, the concept of solving nonlinear model is that we reach current situation to the nearest pareto point. The suggestion of Nonlinear Programming method is paper recovery network design with economic costs 15203280 and environmental effects 20661438.

Proposed Network of Nonlinear Programming Method

Plants are established in zones 5, 8 and 12 and paper supply flow and dispatched paper amount from warehouses to plants are shown in fig. 6. Amount of network economic costs is 15203351 and amount of network environmental costs is 20263248.

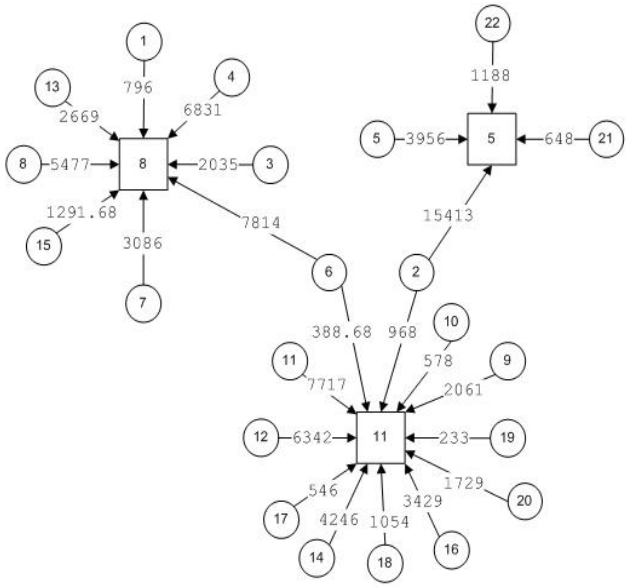

Fig. 6. Recovery network result in Nonlinear Programming method

One of the most important problems in Radial Projection and Nonlinear Programming method is that its solutions might be unachievable in practice. Table 5 shows the results of objective functions of paper recovery network design. It is obvious that the results of STEM method according to its interaction with decision maker solutions are more satisfying than those of other methods.

Table 5
Comparison between used methods for making actual situation network, efficient

Methods	Trade-off between two economic and environmental aspects	
	Costs	Environmental Effects
Radial Projection	15203351	20263248
Nonlinear Programming	15203280	20661438
STEM	21159040	19250630

VI. CONCLUSION

Eco-efficiency literature in reverse logistics network design area doesn't consist of articulated methods in network design with regarding to environmental considerations. In this paper STEM method is used for paper recovery network design in Tehran city of Iran. STEM method is one of the articulated methods to solve multi-objective models. For this purpose, a network design model has been formulated with two objectives including minimization cost and environmental effects. Then, by interacting to a given decision maker solution, an environmentally efficient solution is proposed. This method has compared to other unarticulated method and it has concluded that the results of STEM method are more satisfying than other methods.

REFERENCES

[1] S. J. Cowell, S. Parkinson, "Localisation of UK food production: an analysis using land area and energy as indicators", *Agriculture, Ecosystems and Environment*, vol. 94, 2003, pp. 221–236.

[2] H. Tajik, "Sustainable Development Strategy of External Policies" (in Persian), *congress of Sustainable Development Strategy in execution units of Iran, Environmental Protection Organization*, 2003.

[3] European Union (EU 2003a). 2003. *Directive 2002/96/EC of the European Parliament and of the Council of 27 January 2003 on waste electrical and electronic equipment (WEEE)*, Official Journal, L 037, 13/02/2003, 24-39, Brussels, European Union.

[4] J. Quariguasi Frota Neto, J.M. Bloemhof-Ruwaard, J.A.A.E. van Nunen, and E. van Heck. "Designing and evaluating sustainable logistics networks", *International Journal of Production Economics,* 111, pp. 195–208, 2008.

[5] J. Quariguasi Frota Neto, G. Walther,J.M. Bloemhof-Ruwaard, J.A.A.E. van Nunen, Spengler, T., "A methodology for assessing eco-efficiency in logistics networks", *European Journal of Operational Research*, 2007, doi: 10.1016/j.ejor.2007.06.056.

[6] R. Benayoun, J. Montgolfier, J. Tergny, "Linear Programming With Multiple Objective Functions: Step Method (STEM)", *Mathematical Programming*, pp. 366-375, 1971.

[7] J.M. Bloemhof-Ruwaard, L. Van Wassenhove, , H.L. Gabel, P.M. Weaver, "Environmental life cycle optimization model for the European pulp and paper industry", *Omega-International Journal of Management Science*, 24 (6), pp.615–629, 1996.

[8] G. Huppes, M. Ishikawa,"A framework for quantified eco-efficiency analysis", *Journal of Industrial Ecology*, 9(4):25–41, 2005.

[9] P. Korhonen, S. Stenfors, M. Syrjanen, "Multiple objective approach as an alternative to radial projection in DEA", *Journal of Productivity Analysis*, 20(3):305–321, 2003.

[10] P. J. Korhonnen, M. Luptacik, "Eco-efficiency analysis of power plants: An extension of data envelopment analysis", *European journal of operational research,* 154, pp. 437-446, 2004.

[11] B. Zhang, J. Bi, Z. Fan, Z. Yuan, J. Ge, "Eco-efficiency analysis of industrial system in China: A data envelopment analysis approach", J*ournal of Ecological Economics*, Volume 68, Issues 1-2, pp. 306-316, 2008.