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Designing sustainable recovery network of end-of-life products using genetic algorithm

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ABSTRACT

Sustainable development was articulated by the Brundtland Commission as development that "meets the needs of the present without compromising the ability of future generations to meet their own needs". Consumers and legislation have pushed companies to re-design their logistics networks in order to mitigate negative environmental and social impacts. The objective of this paper is to design a sustainable recovery network, in which economical, environmental and social impacts are balanced. Life cycle analysis (LCA) has been applied to investigate the environmental impact of different end-of-life (EOL) options. Analytical hierarchy process (AHP) has been utilized to calculate social impacts. Next in this research, a three-objective mathematical programming model has been developed to maximize economic and social benefits and minimize negative environmental impacts, simultaneously. Scrap tires have been considered for a case study. Multi-objective genetic algorithm (MOGA) has been applied to find the Pareto-optimal solutions. In the recovery network of scrap tires, each solution corresponds to a different configuration of the network, based on technology type and location of installed recycling plants. These Pareto-optimal solutions will give some trade off information about the three mentioned objectives, so decision makers can assess the economical impact of efforts of improving the social and environmental issues.

1. Introduction

The World Commission for Environment and Development (WCED, 1987) has focused on the need for a sustainable future, and actions to be taken on different levels in the society to change industrial practice and consumption patterns worldwide. Sustainable development must consider economic, environmental and social considerations, simultaneously. These issues illustrate the importance of disciplines as diverse as ecology, economics and sociology in developing a sustainable development perspective (Cowell and Parkinson, 2003). In fact, moving toward sustainable development needs to meet the objectives in three mentioned areas in such a way that:

- Maintain a high and stable level of economical growth and employment.
- Effective protection of the environment.
- Provide social progress which recognizes the needs of every one.

Consumers and governments have been pressing companies to reduce the environmental impact of their product and processes (Thierry et al., 1995). Companies such as 3M, Shell, Amoco and Interface, have long used standard financial indicators to determine their business success. A growing number of firms have begun to use environmental, health and safety (EHS), and social indicators (Veleva and Ellenbecker, 2001). A group of companies has gone further and achieved economic gains from the adoption of environment-friendly logistics networks. IBM, for instance, has profited from its programs to receive end-of-use products, promote second hand items Internet auctions and dismantle equipment as a source of spare parts (Fleischmann et al., 2003). Today, some of the manufacturers in many countries are financially and organizationally responsible for the take-back of their products when they reach the end of their life cycle. The important issue is that the three dimensions of sustainability are almost conflicting. It means that dealing with EOL products needs incur more costs rather than resultant benefits. At the same time waste treatment will be advantageous for the society.

While some of the relevant questions about sustainability have been considered by works on topics such as greener product design, cleaner process technology, product life extension, and environmental management systems, these subjects are not considered from the unifying perspective of sustainability (Linton et al., 2007). Literature into recovery network design is mostly divided in two approaches: minimizing costs (or maximizing profits) and minimizing environmental impact. There is little done integrating these two formulations (see Bloemhof-Ruwaard et al.,

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2004). Social side of sustainability is always ignored in the literature.

In order to move towards sustainability, this paper aims to provide multi-objective mathematical programming model to design of sustainable recovery network of EOL products. The network configuration specifies physical location of facilities and transportation route among them. To design such sustainable network there is a need to consider economical, social and environmental objectives simultaneously. LCA, as a standard tool for environmental assessment, is used to assess environmental impact of different processes incorporated in recovery processes. Eco-indicator (as described in next sections) methodology is applied to quantify environmental impacts. Social issues are almost multidisciplinary and qualitative concerns. AHP (Saaty, 1980) that is popular in multi-criteria decision making (MCDM) methods is suitable to integrate social issues in quantitative decision making. The combinatorial and multi-objective nature of designing sustainable recovery networks requires, besides smart algorithms, parsimonious conceptual models in order to keep the problem CPU-time tractable, without losing its explanatory power (Quariguasi Frota Neto et al., 2008). In recent years, genetic algorithm (GA) has been known to be an extremely robust technique to solve complex multi-objective optimization problems. There is no single optimum solution in multi-objective programming (MOP) model. MOP deals with a set of Pareto-optimal solutions. MOP is denoted by (Steuer and Piercy, 2005):

$$\max\left\{c^1x = z_1\right\}\ldots\max\left\{c^kx = z_k\right\},$$
$$\text{s.t. } \left\{x\in R^n|Ax\le b, b\in R^m, x\ge 0\right\} \tag{1}$$

where k is the number of objectives. A point $x'\in S\subset R^n$ is efficient (Pareto-optimal) if and only if there is no $x\in S$ such that $c^ix\ge c^ix'$ and there is at least one $c^ix<c^ix'$. The efficient set or Pareto-optimal set is the set of all efficient solutions. Since GA works with a bunch of solutions, it is able to capture a population of Pareto-optimal solutions in a single simulation run of algorithm and abrogating the need of repetitive use of a single-objective optimization method to reach the Pareto-optimal set (Deb, 2001). Each solution in Pareto-optimal set can be interpreted as a network configuration. In this paper, multi-objective genetic algorithm (MOGA) (see Deb, 2001) is used to solve the multi-objective mathematical model. Finally, a simple measure is introduced to assess different solutions for network configurations. Scrap tires have been selected as a case study to illustrate this approach.

2. Objectives and limitations

The main objectives of this study can be summarized as follows.

- Using Eco-indicator to quantify environmental impact of each process in product recovery network.
- Incorporating social criteria in recovery network design using AHP method.
- Providing multi-objective mathematical programming model to design recovery network with respect to unifying perspective of sustainability. The objectives are maximizing economical and social benefits and minimizing negative environmental impact.
- Applying GA to explore Pareto-optimal solutions to assess trade-offs among economical, environmental and social impacts of different recovery network configuration.
- Offering a simple measure to guide decision maker in choosing appropriate solution of network configuration. This measure considers decision maker's preferences about economical, social and environmental objectives.

Gathering regional data was the problematic issue in this study. To overcome this, estimation was used to calculate parameters needed in the model. In some cases, such as acquiring environmental impact, results of related papers were applied as a reference.

3. Designing sustainable recovery network

Fleischmann et al. (2000) denotes five groups of activities that appear to be recurrent in product EOL recovery networks: collection, inspection/separation, re-processing, disposal and re-distribution. Each of these activities has economical, environmental and social impact that should be considered in the recovery network configuration. It needs to be mentioned that transportation plays a key role in moving from one step to another, so cost and environmental impact of transportation are an important index in the network design. Cost/profit has traditionally been the most important factor in network configuration decision making (see Fleischmann et al., 2000). However, environmental and social considerations are also concentrated in the literature survey. The next two sections, based on literature survey, describe how to quantify environmental and social impacts to construct corresponding objective functions.

3.1. Environmental impact

LCA is a tool for quantitative assessment of materials, energy flows and environmental impacts of products, services and technologies. LCA is sometimes presented to be the tool for environmental product management (Krozer and Vis, 1998). There is now a widespread agreement amongst industry, government and other stakeholders, that environmental issues and their impacts must be considered from a life cycle perspective. Several researchers have adopted LCA-based methodology to characterize environmental considerations with respect to an array of pollutants (Powell et al., 1996).

LCA starts with (1) definition of the functional unit, then (2) a quantitative inventory of all inputs and outputs is performed, followed by (3) classification and impact assessment and, finally, (4) evaluations. The technique of inventory analysis has been used for quite some time and comprehensive database is available. It is the less controversial part of the framework. The interpretation of the impact assessment is another matter. Currently the impact assessment data is processed using characteristic transformation or weighted multiplication to obtain an impact index (see Quariguasi Frota Neto et al., 2008). The process is usually very complicated as well as time consuming and can only be performed adequately by an expert of environmental management (Chiu et al., 2008). To overcome this cumbersome process and to provide pertinent information in a timely fashion, researchers in the Netherlands proposed a method of using one index to represent the environmental impact of a product or a manufacturing process. The index is based on the concept of an "ecological foot print" and is now widely accepted. The current version is Eco-indicator 99 (Goedkoop and Spriensma, 2001). This index utilizes data from inventory analysis and transforms these data into three categories in a unified way. The categories are human health, ecological quality, and resource consumption. These three quantities are then combined in a weighted manner (40%, 40% and 20% for human health, ecological quality, and resource consumption, respectively).

Finnveden and Ekvall (1998) have declared that LCA should be used in deciding about issues such as which waste management option, is to be preferred. In this paper LCA is integrated in recovery network design. Since LCA is a quantitative method of environmental assessment of any process, it is useful to construct the mathematical model in optimization. Regarding this, the single indicator obtained from the Eco-indicator methodology is used to construct the environmental objective of mathematical programming developed to achieve sustainable recovery networks. Such indicator is always proportional with the mass of each process, i.e., the environmental impact of processing one unit of inputs is indicated by corresponding Eco-indicator (see Ministry of Housing, Spatial Planning and the Environment, 2000-Netherland).

To the best of our knowledge, this is the first attempt to reconcile the Eco-indicator in recovery network design.

3.2. Social impact

Social responsibility (SR) is defined as "the continuing commitment by business to behave ethically and contribute to economic development while improving the quality of life of the workforce and their families as well as of the local community and society at large" (WBCSD, 1999). Indicators for the social dimension of sustainability have, thus far, concentrated on a company's own activities. Ethical indicators cover aspects such as stakeholder inclusion; preservation of cultural values and benefits to communities surrounding a company's operation; consistency of employment conditions and health and safety standards for all operations regardless of their location and leaving the environment in a condition likely to be acceptable to future generations and not creating problems, such as toxic or radioactive wastes, for which solutions are not known (Clift, 2003). Veleva and Ellenbecker (2001) have reviewed existing literature about indicators of sustainable production and presented core indicators of sustainable production. They have considered social justice and community development as one of six main aspects of sustainable production. It means that communities around workplaces should be respected and enhanced economically, socially, culturally and physically. Equity and fairness should be promoted. The goal of this principle is to increase employment opportunities for the local community and increase community–company partnerships. Another important category in social considerations is workers. As a principle, workplace should be designed to continuously minimize or eliminate physical, chemical, biological and ergonomic hazards.

Above notes demonstrate that the field of SR is a truly multidisciplinary and multi-stakeholder area of inquiry. To capture this "holistic" phenomenon, International Standard Organization (ISO) created a balanced, multi-stakeholder working group on SR that was charged with development of "International Guidance Standard on Social Responsibility—ISO 26000" (ISO/TMB/WG/SR, 2006). Even though ISO 26000 development is still under way, several important issues about the standard were already decided. Firstly, the scope of the standard proposed structure and key components were agreed upon (Castka and Balzarova, 2008). Table 1 shows these preliminary agreements.

In this paper, social impacts of recovery network are the main concerns. Carter and Jennings (2002) have mentioned that the logistics social responsibility (LSR) can be classified into six topics, namely environment, ethics, diversity, working conditions and human rights, safety, philanthropy and community involvement.

De Brito (2003) in her thesis, has said that reverse logistics can be seen as part of sustainable development. In exploring social impact of reverse logistics, she draws attention to employment: "We do know that some of the recovery activities like recycling are labor intensive. Studies have indicated that recycling activities create 5 to 7 times the number of jobs than incineration and more than 10 times than land filling operations. The number of people working in recovery activities is estimated to exceed 3 millions. Besides this, the European Commission realizes that recovery activities offer an opportunity to create new distinct jobs, which are not going to be a copy of already existing employment. Furthermore, these jobs are a privileged vehicle for reintegration of workers in professional life. The number of social jobs in recycling and reuse has been estimated to surpass 35,000 in Western Europe".

Table 1
ISO 26000:key components. *Source*: Castka and Balzarova (2008).

Human rights (universal declaration of human rights, ILO core conventions)
Workplace and employee issues including occupational health and safety
Unfair business practices including bribery corruption and anti-competitive practices
Organizational governance
Environmental aspects
Marketplace and consumer issues
Stakeholder involvement
Social development

Ahluwalia and Nema (2007) have considered risk perceived by the public as a factor to be minimized in computer waste management. Perceived risk for various management options for each waste type has been estimated using expert opinion. But they have only regarded to the health risk caused by hazardous materials which can influence workers and other people who live around the waste treatment activities.

As a matter of fact, the social sustainability dimension has largely been absent in OR contributions, with the exception of some areas investigating the health impacts of institutional operations (White and Lee, 2009). Usually, the criteria in social aspect of sustainable production, are conflicting and not equally important. Based on qualitative nature of social impacts, a MCDM approach is suitable. In this paper the concept of AHP (Saaty, 1980) was used to get a single indicator that describes social impact of different EOL alternatives. Normalized weight obtained from AHP is used as social single indicator of different EOL activities. This indicator indicates the social impact of treating EOL product in each EOL option. For example if EOL type 1 is selected as a recovery process, its social impact should be considered in calculating social objective function.

4. An illustrative case study: tire recovery network design

By facilitating the secure transport of materials, goods and passengers, tires can be considered an asset for society. Nevertheless, tires can cause environmental pressure in many ways, in different stages of the life cycle of tires, including production, consumption, and solid waste management (Beukering and Janssen, 2001). Due to the increased number of vehicles, the 'mountain' of used tires has grown dramatically during the last decades. Every year, approximately 800 million scrap tires are disposed around the globe. This amount is expected to increase by approximately 2% each year (UNCTAD, 1996). The resulting life cycle phase contributions to the global environmental impact of the tire (PRé Consultants B.V., 2001) shows that the end-of-life phase constitutes an important factor to reduce the environmental impacts caused by production, depending on the disposal technologies used to process the tires. Reusing, recycling, retreading, incineration with energy recovery and disposing in landfills are the EOL alternatives for scrap tires.

(1) Reuse: scrap tires are regularly used in agriculture and civil engineering applications in a variety of ways. For the list of applications see Sunthonpagasit and Hickman (2003).
(2) Recycling: recycling of scrap tires can be classifies in two groups:
  - Reclaiming of the rubber content of the scrap tires can be done using oil, water, and reclaiming agents. Reclaimed rubber can be blended with virgin compounds to produce rubber feedstocks.
  - Grinding scrap tires into crumb rubber while removing steel and fiber. There are two main technologies for scrap tire grinding: *mechanical pulverization* (Ambient) that is a mechanical grinding system that operates at room temperature and tears

the tire material apart. The process is called ambient, because all size reduction steps take place at or near ambient temperatures, i.e. no cooling is applied to make the rubber brittle. Another technology is *Cryogenic pulverization* that is a freezing process where scrap tires are frozen at very low temperatures by liquid nitrogen, and then shattered like breaking glass. The advantages of this kind of process are mainly the high quantity and high quality of the rubber that can be recovered (Corti and Lombardi, 2004). In general, a 'high quality of crumb' means low fiber content (less than 0.5% of total weight), low metal content (less than 0.1%), and high consistency (Sunthonpagasit and Duffey, 2004). The most frequent recycling activities consist of the use of vulcanized rubber in sport surfaces and floors, as a construction material and as an additive for bitumen in road surfaces (Ferrao et al., 2008).

(3) Retreading is a method by which worn tires with usable carcasses are given a second life. In the retreading process, the remaining tread rubber is removed by a grinding process called buffing, and then replaced with a new tread. Passenger tire retreading is decreasing because of low prices of new tires (Sunthonpagasit and Hickman, 2003).

(4) Discarded tires are utilized for their energy value. Applications include use as fuel in power plants, tire manufacturing facilities, cement kilns, and pulp and paper production. However, the burning of whole discarded tires requires a relatively sophisticated high-temperature combustion facility to keep emissions within environmental limits and use of equipment capable of handling whole discarded tires and feeding them into the combustion chamber (Jang et al., 2004). Depending on the technology used, cement kilns can burn tires up to 20–25% of their total fuel consumption. A major advantage of using tires in cement kilns is that the process does not generate solid waste because the ash residues from the combustion are bound to the final product.

(5) Disposing in landfill is another EOL option, however, the European Commission's Landfill Directive (European Directive 1999/31, Landfill Directive) has banned the disposal of whole tires to landfill by 2003, and shredded tires by 2006. Furthermore, the European Directive 2000/53 (European Directive 2000/53, End of Life Vehicle), requires that the 80% in weight of an end life vehicle is reused or recycled, by 2006, and the processes concerned with scrap tires has played an important role in achieving this target. The impacts resulting from the tire landfills are mainly due to the eco-toxicity associated with the leaching of metals as well as from the leaching of different ingredients such as stabilizers, flame retardants, colorants, and plasticisers, which are mixed with rubber during compounding (Ferrao et al., 2008).

In spite of governmental regulations for waste treatment in Iran, about 70% of scrap tires disposed in stockpiles. Only 30% of discarded tires are processed in retreading (19 companies) and recycling plants. There are four units for tire recycling. Two of them produce pulverized tire and others produce rubber reclaim. The discarded stockpiles have negative environmental impact. The country also losses economical and social benefits, which can be achievable from treating these scraps (Samadian, 2006). In this paper, a mathematical model to design the sustainable recovery network of scrap tires is provided. The main activities influencing recovery network configuration are listed in Table 2.

4.1. Recovery network design

We look for sustainable configuration of tire recovery network. In doing so, it is assumed that government is the trustee of this network in each tier of logistics network. Although there are some existing units for recycling, the country has a great potential to install new facilities for EOL management of tires. Based on regional feasibility studies (Samadian, 2006), because of low quality specification, reclaim rubber has not more application, yet. Retreading companies also work on below capacity because customers find it uneconomical. Three types of treatments for EOL management of tires were selected.

Table 2
The main activities influencing scrap tire recovery network configuration.

Type	Description
Collection of scrap tires	Scrap tires are disposed in different locations such as repair shops and nature. There is a need to collect them in dedicated collection centers.
Separation	Only some of scrap tires with specific technical characteristics can be retrodden while others are suitable for recycling or incineration for energy recovery.
EOL treatment processes	There are different technologies for EOL management of tires such as: retreading, mechanical and cryogenic pulverization, pyrolysis, and incineration in cement kiln.
Transportation	Transportation of discarded tires to collection centers and transportation of inspected ones to each EOL treatment factory.

- Mechanical pulverization.
- Cryogenic pulverization.
- Incineration in cement kiln.

This paper assumes that the location of collection centers and the amount of tire stocks are known. Therefore location and type of scrap tires processing plants should be found as well as their shipment quantity from collection centers to each plant (including pulverization and cement plants). There are candidate positions for installing new recovery facilities for tire recycling and also many cement factories in different locations of the country that can use scrap tire, as a fuel substitute. To construct a mathematical programming model for network design, there is a need to explore economic, environmental and social factors of all activities influencing recovery network of scrap tires.

4.1.1. Estimation of economic impact

EOL products are no longer considered as wastes and in fact could be quite beneficial economically. This could be emphasized by the case of scrap tires. Processing scrap tires produce valuable products such as crumb rubber that has international price and customers. Acquiring such benefits needs two main expenditures that are: capital cost of installing and operating new factories and cost of transportation. These economical parameters have been considered to construct profit objective function that should be maximized.

4.1.2. Estimation of environmental impact

Corti and Lombardi (2004) have applied LCA to compare 4 processes for EOL treatment of tire. The processes are: combustion in a conventional waste-to-energy process; substitution of conventional fuel in the cement clink process and two different hypotheses of reuse as filling material based on a cryogenic pulverization process or on a mechanical pulverization process. Their analysis is based on 1 ton (1000 kg) of tires assuming all tires have equal properties. They then used the Eco-indicator 95 methodology to assess the relative environmental impacts of each of the four end-use options in terms of 'eco-points'. Other studies in this area are the work conducted by the IVL Swedish Environmental Research Institute Ltd. (Aman, 2006) and the Continental company (Kromer et

Table 3
Social issues.

Issues	Description
Employment	Different EOL option creates different number of job opportunity.
Damage to workers	It means working conditions may expose workers to hazardous environment. For example, Health hazards of chronic nature due to long term exposure to chemical elements. The damage of emissions was excluded here.
Product risk	Consumers perceive different risk in consuming different recycled materials. For example retreading tires may have greater risk in transportation.
Local development	Installing new facilities in less developed areas can cause community development that is an important issue in government social responsibilities.

al., 1999), but they have not applied Eco-indicator method to assess environmental impact.

Calculating the exact effect of environmental impact of each EOL option is not the purpose of this study. Relative environmental impact of EOL options is sufficient, so the Corti and Lombardi's result is used for evaluating environmental impact. However, they employed the older version of the Eco-indicator method.

4.1.3. Estimation of social impact

The issues in corporate social responsibility and logistics social responsibility were presented to the panel of experts in tire industry in Iran. With respect to important concerns of developing countries such as Iran, four criteria in social considerations are finally chosen. These criteria are briefly described in Table 3.

The AHP hierarchy can be constructed as shown in Fig. 1. The important factor is that local development score is related to the geographical location of recovery facilities, so different candidate locations with the same facilities can have different social impacts. The final normalized weight for different locations can be included in mathematical representation of social objective function. A broader discussion of social impact of different EOLs is given in the numerical example.

4.2. Mathematical formulation

In this section a multi-objective programming model is provided. The objectives are the maximization of economical and social benefits and the minimization of environmental impacts. Decision variables are about installing or not installing the plants in the candidate locations. Shipment quantity from collection centers to each installed plant is another decision variable in this model. The multi-objective formulation is presented below:

Indices and parameters:

I	index set of collection centers
J	index set of EOL options (different plants)
K	index set of output of different type of processing
L	index set of potential plant sites
M	index set of existing cement factories
H	index set of capacity levels available to the potential facilities
Z	index set of social criteria
EI_j	environmental impact of processing 1 ton of scrap tire using option j
C_j^h	fixed cost per unit of time for opening and operating plant j with capacity level h
S_{jk}	sale price of product k of plant j
α_{jk}	percent of product k obtained from plant j per ton of input processing
ST_i	quantity of scrap tires collected in collection center i per unit of time
e_j^h	capacity with level h for the potential plant at site j
N_m	maximum need of scrap tire in cement plant m per unit of time
d_{il}	distance between collection center i and potential plant site l
$\bar{d}_{im}$	distance between collection center i and cement plant site m
C^T	cost of shipping 1 ton of scrap tire per kilometer
EI^T	environmental impact of shipping 1 ton of scrap tire per kilometer
LD_{jl}^h	local development score of potential plant j at site l
EM_{jl}^h	employment score of potential plant j at site l
DM_{jl}^h	damage score of potential plant j at site l
PR_{jl}^h	product risk of potential plant j at site l
W_{ld}	normalized weight of local development
W_{em}	normalized weight of employment
W_{dm}	normalized weight of hazardous working conditions
W_{pr}	normalized weight of product risk

Variables:

X_{ijl}	quantity of shipments from collection center i to plant j at site l
Y_{im}	quantity of shipments from collection center i to cement plant m

$$V_{jl}^{j} = \begin{cases} 1 & \text{if plant } j \text{ with capacity level } h \text{ located at site } l \\ 0 & \text{otherwise} \end{cases}$$

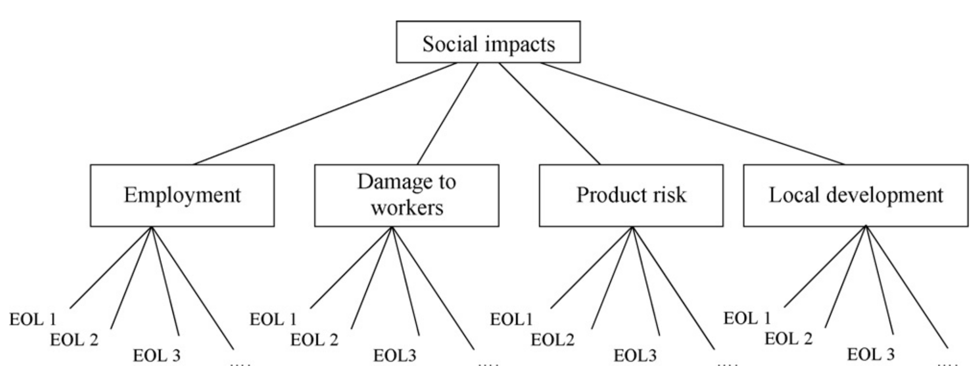

Fig. 1. Hierarchy of decision making for social impact of given EOL options.

In terms of the above notation, the problem can be formulated as follows:

$$\mathrm{Max}\, Z_1 = \sum_i \sum_j \sum_l \sum_k X_{ijl}\alpha_{jk}S_{jk} - \sum_j \sum_h \sum_l C_j^h V_{jl}^h - C^T \times \left[\sum_i \sum_j \sum_l X_{ijl} d_{il} + \sum_i \sum_m Y_{im}\bar{d}_{im} \right] \quad (2)$$

$$\mathrm{Min}\, Z_2 = \sum_i \sum_j \sum_l X_{ijl}\mathrm{EI}_j + \mathrm{EI}^T \left[\sum_i \sum_j \sum_l X_{ijl} d_{il} + \sum_i \sum_m Y_{im}\bar{d}_{im} \right] \quad (3)$$

$$\mathrm{Max}\, Z_3 = \sum_j \sum_h \sum_l (W_{em}\mathrm{EM}_{jl}^h + W_{ld}\mathrm{LD}_{jh}^l + W_{dm}\mathrm{DM}_{jl}^h + W_{pr}\mathrm{PR}_{jl}^h)V_{jl}^h \quad (4)$$

Subject to:

$$\sum_j \sum_l X_{ijl} + \sum_m y_{im} \le \mathrm{ST}_i; \quad \forall i \quad (5)$$

$$\sum_i X_{ijl} = \sum_h V_{jl}^h e_j^h; \quad \forall j, l \quad (6)$$

$$\sum_h V_{jl}^h \le 1; \quad \forall j, l \quad (7)$$

$$\sum_i y_{im} \le N_m; \quad \forall m \quad (8)$$

$$X_{ijl} \ge 0; \quad \forall j, l \quad (9)$$

$$V_{jl}^h \in (0, 1); \quad \forall j, l, h \quad (10)$$

The model maximizes profits, minimizes environmental impact and maximizes social impact based on (1), (3) and (4), respectively. Constraint set (5) represents capacity restriction of the collection centers. Constraint set (6) guarantees that the total shipments of scrap tires to an opened plant should be equal to the capacity of the plant. This is due to the assumption that operating the plant under base capacity is uneconomical. Constraint set (7) represents that a plant at each location can be assigned at most one capacity level. Constraint set (8) ensures that the total shipments of scrap tires to an existing cement plant do not exceed the maximum requirement of the plant per unit of time. Finally, constraints in set (9) enforce that the corresponding decision variables are always a positive value and (10) imposes the integrality restrictions on the binary variables.

4.3. Solution method

In this section, as described earlier, MOGA is used to find different Pareto-optimal solution for the developed mathematical model. To obtain the corresponding Pareto-set, the NSGA-II algorithm (Deb et al., 2002) is adapted. The following sections describe in details how the MOGA has been implemented.

4.3.1. Representation

The most important issue that should be determined is the type and the location of the installed plants. If these are determined, the remaining important decision is the shipment quantity of scrap tires from collection centers to the installed plants. The latter can be solved easily as a classical transportation problem.

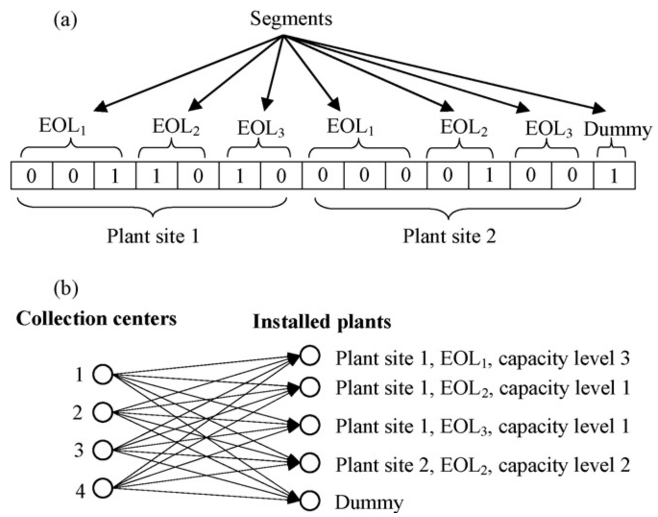

Fig. 2. Chromosome representation (a) and corresponding transportation problem (b).

A gene in a chromosome is characterized by two factors: locus that is the position of the gene within the structure of chromosome, and allele, the value the gene takes. In this paper, the position of a gene represents the EOL type (as described in Section 4.1), the location and the capacity of the potential plant sites while its value represents the installation of corresponding plants, i.e. '1' indicates the installation and '0' means no installation of corresponding plant. So, the solutions could be represented by a chromosome that has a number of segments corresponding to the number of EOL options and the number of the potential plant sites. Each segment can have a number of binary genes with respect to capacity levels. In each segment, only one gene can have value of '1'. A gene is also added at the end of the chromosome that relates to dummy location in transportation problem. In case that total scrap tires of collection centers exceeds the capacity of installed plants dummy gene will receive the surplus scrap tires, which is not desirable for the purpose of this problem. The dummy location can be seen as landfill site. Costs, environmental and social impacts have been considered for dummy (landfill) site. This representation needs a repair mechanism to obtain feasible solutions after applying classical genetic operators. The infeasibility can only occur when the total capacity of installed plants exceeds the total scrap tires available within collection centers. In such cases repair mechanism randomly selects a gene with value '1' and modifies it to '0' until there is a balance between the supply and demand of scrap tires.

An example for representation and its corresponding transportation problem are illustrated in Fig. 2. In this example, we have assumed that there are 4 collection centers, 2 potential plant sites and 3 EOL options. Each EOL option has 3, 2 and 2 capacity levels, respectively. To decode this chromosome there is a need to solve a classical transportation problem, in which, source nodes are the collection centers and destination nodes are installed plant with definite types and capacities. For the example in Fig. 2, first seven genes of the chromosome belong to plant site 1. The 3rd gene with the value of 1 indicates that a plant of type EOL_1 should be installed in its third capacity level. Similarly, the 12th gene shows the plant of type EOL_2 should be installed in its second capacity and so on.

4.3.2. Fitness evaluation

An important issue in multi-objective optimization is how to determine the fitness value of the chromosome for survival. The fitness value of each individual reflects how good it is based upon its achievement of objectives. Each chromosome has three fitness values with respect to three objective functions. For each chromosome solution of the corresponding transportation problem specifies the quantity and costs of shipments from all collection centers to installed plants. Adding installation cost and incomes of outputs, leads us to compute profit objective function. Distance and load of transportation are multiplied by environmental impact of transportation (based on Eco-indicator index) to estimate the environmental impact of transportation. Capacity of installed recovery plants and Eco-indicator of each EOL option are employed to determine the environmental impact of recovery processes. Adding both mentioned impacts will result in the environmental objective function. Social objective function is easily calculated based on the type of installed plant, plant location and corresponding social factor obtained by AHP method.

4.3.3. Crossover and mutation

The segment-based crossover operator of Altiparmak et al. (2006) is applied which is based on uniform crossover. In this operator, each segment of offspring is randomly selected with equal chance among the corresponding segments of parents. Crossover operator utilizes a binary mask (Altiparmak et al., 2006). Its length is equal to the number of segments of a chromosome. '0' means that corresponding segments of parents will not transfer their genetic materials to each other while '1' means otherwise. The operator creates two offsprings. Similar to crossover operator, segment-based mutation has been applied based on the binary mask. Selected segment is mutated using swap operator. This operator selects two genes from the corresponding segment and exchanges their places.

4.3.4. Selection mechanism

In the proposed GA, initial population is randomly generated and Pareto-optimal set is created by non-dominated sorting on the initial population. Non-dominated sorting creates a number of fronts of non-dominated solutions in which first front include solutions that cannot be dominated by other solutions. Excluding first front solutions, second one contains solutions that cannot be dominated by other remaining solutions and so on. To build new population, the algorithm start from first front and select solutions until the number of selected solutions equals to the population size. If the number of solutions in first front be less than the population size the algorithm go through the other fronts, respectively, to choose new solutions. Crowding distance measure (Deb et al., 2002) will be applied in case that there are more than one alternative to choose for new population. Pareto-optimal set is updated by new individuals obtained with genetic operators in each iteration.

4.4. Example problem

Four large Iranian cities were selected to be included in the developed model. These cities with due to their large populations are the main point of scrap tire generation and also potential candidates for installing recycling facilities. In Iran, there is one car for 8–9 persons, one scrap tire for 5–6 persons and 3.6 kg of scrap tire per capita per year (Samadian, 2006). Based on this information, Table 4 shows the estimation of discarded scrap tires in each city per year.

There are also several cement plants in the selected cities that have the highest priority for using scrap tires as a fuel substitute. Burning of 1 kg tire creates energy equal to 32 MJ (million joules). Average energy need for producing 1 ton of cement is 5 MkJ (million kilo joules), so producing 1 ton of cement needs 0.2 ton of tire approximately. It is assumed that at most 20% of energy requirements of a cement plant can be accommodated by scarp tires. Based on these data maximum annual scrap tire requirements of cement

Table 4
Example data.

City	Scrap tire per year (ton)	Scrap tire needs per year				
		Mechanical			Cryogenic	Cement
		Production level				
		1	2	3		
Tehran	21,600	6000	12,000	18,000	6000	10,800
Mashhad	10,800	6000	12,000	18,000	6000	5,400
Esfahan	9,000	6000	12,000	18,000	6000	4,500
Shiraz	5,400	6000	12,000	18,000	6000	2,500

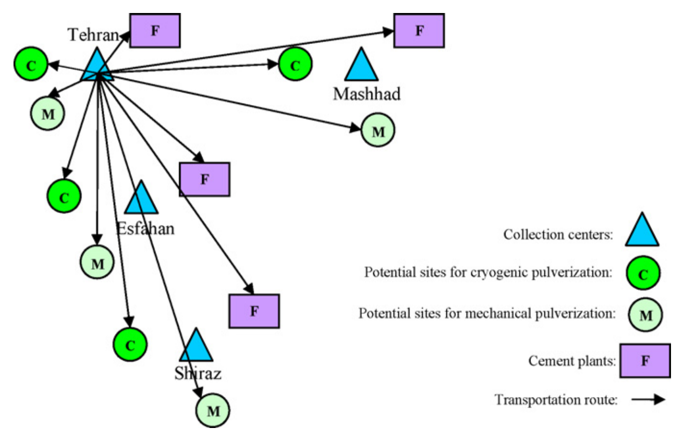

Fig. 3. Illustration of example problem.

plants can be calculated. There is a need to install a feeding system to feed scrap tires to cement kiln that costs approximately 1770 billion Rials (local currency, 2007 prices). Cement plants can save 100 Rials per kilogram using scrap tires instead of conventional fuel (Samadian, 2006). One candidate cement plant in each city is considered to use at most 50% of generated scrap tires of that city as the fossil fuel substitute. Three levels of production for mechanical pulverization are also considered. These levels of production could also be translated as number of plants. For example second level means that two plants could be installed. Although product quality of cryogenic pulverization is better than mechanical one, production costs and its negative environmental impact is higher (Corti and Lombardi, 2004). So one level of production for cryogenic pulverization is considered. Fig. 3 summarizes the example described here. Possible transportation route for shipment of scrap tires from Tehran collection center to the potential EOL plant site is shown in this figure via arrows. There are similar routes for other collection centers.

Average global price for crumb rubber that is the major output of mechanical and cryogenic pulverization has been adopted for the purpose of calculation. Due to the superior quality of the cryogenic pulverized product, its price has been considered slightly higher than mechanical one. Processing 1 ton of scrap tires will result in 0.6 ton of crumb rubber (Samadian, 2006). It is also assumed that there is no limitation on the sales of final crumb rubber.

To estimate the social impact of each EOL option, AHP methodology was employed based on experts' opinions. Table 5 gives the

Table 5
Relative weight of criteria.

Criteria	Normalize weight
Employment	64.7%
Damage to workers	7.3%
Product risk	6.6%
Local development	21.4%

Table 6
Social indicator of each EOL option obtained from AHP.

EOL specifications			Social indicator (×1000)
Type	Location	Capacity level	
Mechanical	Tehran	1	36
Mechanical	Tehran	2	57
Mechanical	Tehran	3	86
Cryogenic	Tehran	1	35
Cement	Tehran	1	22
Mechanical	Mashhad	1	34
Mechanical	Mashhad	2	61
Mechanical	Mashhad	3	89
Cryogenic	Mashhad	1	36
Cement	Mashhad	1	22
Mechanical	Esfahan	1	36
Mechanical	Esfahan	2	64
Mechanical	Esfahan	3	93
Cryogenic	Esfahan	1	38
Cement	Esfahan	1	22
Mechanical	Shiraz	1	38
Mechanical	Shiraz	2	69
Mechanical	Shiraz	3	100
Cryogenic	Shiraz	1	40
Cement	Shiraz	1	22

relative weight of social criteria. Final results of evaluation are given in Table 6. This table demonstrates the quantitative social impact of each EOL option. Expert Choice software (Expert Choice Inc., 2000) has been used for these calculations (for details see Appendix A). As Table 5 shows, employment and local development have received higher importance. The results of Table 6 are obtained based on pairwise comparison matrices explained in Appendix A. For doing so, it has been considered that cryogenic pulverization plant almost creates equal job opportunities compare to mechanical one and these two creates more jobs compare to fuel substitute alternative. The outputs of pulverization type of EOLs can be used for producing plastic products. As mentioned above, recycled rubber obtained from cryogenic process has better quality compare to the mechanical one. Therefore, the higher the quality of the product, there will be less risk of any failure. Due to the iron content of the scrap tires the quality of the cement will be improved (Corti and Lombardi, 2004). Therefore using scrap tires as a fuel substitute could be quite beneficial. Cryogenic and pulverization have similar working conditions with minimum workers intervention. This is because of automatic nature of production line (Samadian, 2006). A conventional feeding system and certain number of workers are required to provide tires to cement kiln. This is the only part of the worker involvement in this EOL option in which there is no significant possible hazards. The most important issue in local development is the capital investment. With regard to this argument, it can be easily concluded that provision of fuel substitute has no significant contribution to the local development. Installing plants in less developed cities contributes more to local communities' development. So installing a similar plant in different locations can initiate different social impact for the society as a whole. As far as development is concerned, cities of Tehran, Mashhad, Esfahan and Shiraz have been ranked in descending order, respectively. Table 7 summarizes the other parameters used in this example problem.

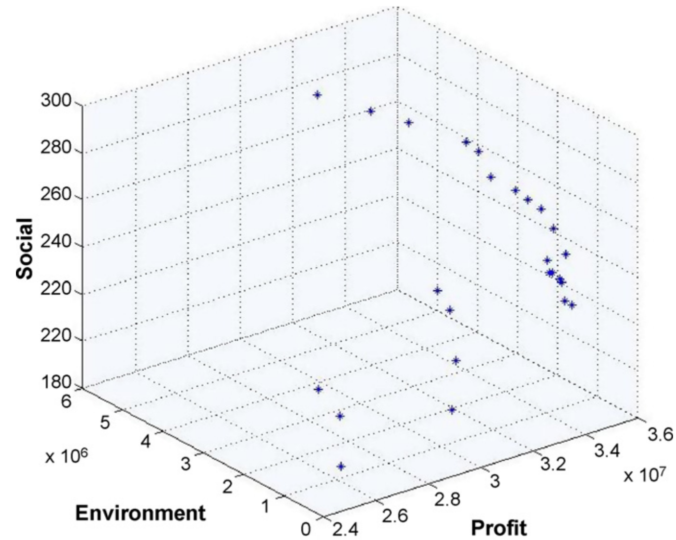

Fig. 4. Pareto-optimal solutions.

Table 8
Optimum solution regarding only profit objective function.

EOLs specification			Objective function values		
Location	Type	Capacity level	Profit	Environment	Social
Tehran	Mechanical	3	34,637,459	754,794	221
Mashhad	Mechanical	2			
Esfahan	Mechanical	1			
Shiraz	Mechanical	1			

MOGA (as described earlier) was applied to solve this example problem. The algorithm has been coded in MATLAB 6.5.1 (The Mathworks Inc., 2004). We set crossover rate, mutation rate and population size as 0.7, 0.1 and 100, respectively. These parameters had been determined after preliminary experiments. The algorithm was stopped after 150 generations. Pareto-optimal solutions of given example are depicted in Fig. 4 (social objective function has been multiplied by 1000). It needs to be mentioned that the environmental objective function should be minimized at the same time profit and social objective function should be maximized. Each star in Fig. 4 corresponds to a definite network configuration. The solution method found 25 different solutions for network configuration (the detail of theses solutions have been given in Appendix B).

In order to show how the achieved solutions correspond to decision makers' preferences, the following steps are introduced:

(1) Ideal point has been calculated. To find Ideal point, Lingo software (Lindo systems Inc.) was utilized to solve the single objective programming model considering each objective function individually. The optimum objective value of each single optimization model constructs the elements of the Ideal point vector (see Tables 8–10). Ideal point elements have been shown in bold font in each table. Regarding to Table 8, profit objective tends to utilize more the mechanical pulverization plant. With respect to environmental objective function, Table 9

Table 7
Social, environmental and economical data for EOL options.

EOLs	Opening and operating cost per year for base capacity level (1000 Rials)	Profit of 1 ton of output (1000 Rials)	Environmental impact of 1 ton of processing
Mechanical	2,200,000	1200	0.278
Cryogenic	2,650,000	1260	42.543
Fuel substitution	425,000	100	−8.1

Table 9
Optimum solution regarding only environmental objective function.

EOLs specification			Objective function values		
Location	Type	Capacity level	Profit	Environment	Social
Tehran	Mechanical	2	25,359,663	476,567	209
Mashhad	Mechanical	1			
Esfahan	Mechanical	1			
Shiraz	Mechanical	1			
Tehran	Cement	1			
Mashhad	Cement	1			

Table 10
Optimum solution regarding only social objective function.

EOLs specification			Objective function values		
Location	Type	Capacity level	Profit	Environment	Social
Tehran	Mechanical	1	31,588,886	5112127	281
Esfahan	Mechanical	1			
Shiraz	Mechanical	1			
Tehran	Cryogenic	1			
Mashhad	Cryogenic	1			
Esfahan	Cryogenic	1			
Shiraz	Cryogenic	1			
Shiraz	Cement	1			

demonstrates that incineration in cement plant is also a suitable EOL option. Clearly, social objective function tends to install the higher number of pulverization plants especially in less developed locations. This is due to the higher importance of employment and local development criteria.

(2) Weighted percent of deviation (WPD) was defined for solution i as Eq. (11):

$$\mathrm{WPD}_i = \sum_{j=1}^{3} \left(W_j \times \frac{\left| f_j^{(i)} - f_j^* \right|}{f_j^*} \right) \tag{11}$$

This measure calculates the weighted distance between a Pareto-optimal solution and the Ideal point. Where W_j denotes the weight of objective function j, which relates to the decision maker's opinion. Weights correspond to the importance of the objective functions. $f_j^{(i)}$ is the jth objective function value of solution i and f_j^* is the jth objective function value of ideal point. Since different objective function has different scale, the distances have been normalized via dividing by Ideal point value. In WPD all deviations are normalized and it gives good insight into the quality of the corresponding Pareto-optimal solution. The lower is the values of WPD, the more it agrees with the decision maker's preferences.

Different sets of W_j were considered and WPD were calculated for the solutions in Pareto-optimal set of the example (see Appendix B). Fig. 5 depicts the results.

In Fig. 5, the numbers allocated to the data keys (bottom of the chart) specify the different sets of W_j. The numbers relates to the weight of the profit, environmental and social objective functions, respectively. In view of the fact that differences among the environmental impact of EOL options are high, a little change in network configuration cause considerable change in environmental objective function. This is further emphasized in Fig. 5, where the weight of environmental objective function increases WPD rises accordingly. Social objective is almost aligned with profit. This is due to the fact that more capital investment creates more profit and job opportunity at the same time contributes to local development. In all data series, there are solutions that have the lowest *WPD*. These solutions are closely matched to the decision maker's preferences. Regarding *WPD*, solution numbers 16–20 are dominated in different sets of W_j. The negative environmental impacts of these solutions are very high as well as their social benefits. This is due to installation of more plants particularly cryogenic ones.

To give information about solutions and corresponding network configuration, solution numbers 1, 9, 12 and 22 were selected among the Pareto-optimal solutions because of the space limitation. These selected solutions almost have the lowest WPD value among different sets of W_j. Table 11 gives objective value, type, location and capacity level of installed plants, and also source node for and shipment quantity to each location. WPD has been calculated based on 0.8, 0.1 and 0.1 for the weights of profit, environmental and social objective functions, respectively. Since profit objective value in solution 1 equals to the Ideal value and the weight of the profit is the highest, this solution seems to be the best solution in the Pareto-optimal set. Its WPD is also the lowest one. So, decision makers based on their preferences about the importance of different objectives can choose a solution for sustainable recovery network configuration.

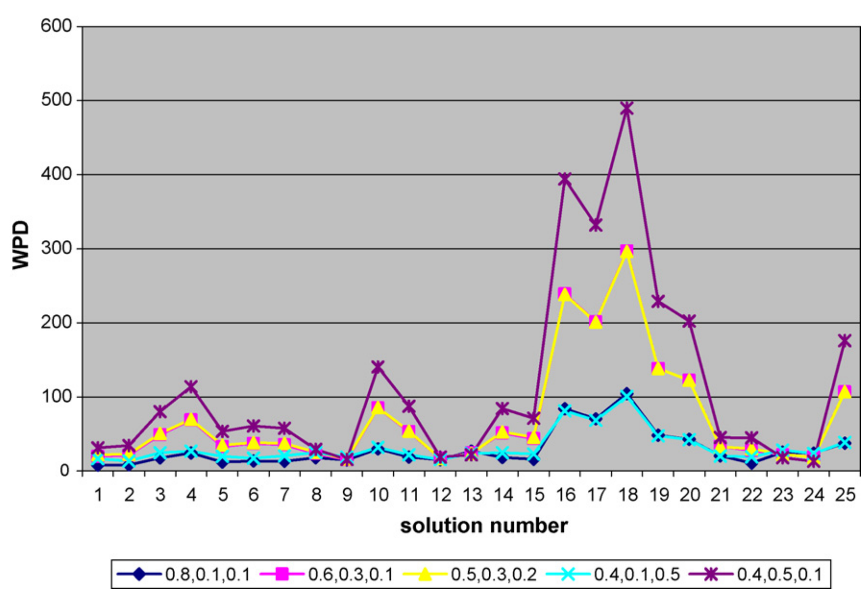

Fig. 5. WPD for all Pareto-optimal solutions.

Table 11
Outputs of sample solutions.

Solution#	Plant location	EOL type	Capacity level	Source and shipment quantity				Objective value
				Tehran	Mashhad	Esfahan	Shiraz	
1	Tehran	Mech.	3	18,000				Profit = 34,637,459,
	Mashhad	Mech.	2	1,200	10,800			Environ. = 754,794,
	Esfahan	Mech.	1			6000		Social(× 1000) = 221, WPD_i = 7.9%
		Cement	1					
	Shiraz	Mech.	1			600	5400	
9	Tehran	Mech.	3	18,000				Profit = 34,547,459,
	Mashhad	Mech.	1		6,000			Environ. = 1,008,384,
		Cement	1	600	4,800			Social(× 1000) = 230, WPD_i = 14.8%
	Esfahan	Mech.	1			6000		
	Shiraz	Mech.	1			600	5400	
12	Tehran	Mech.	3	18,000				Profit = 29,910,867,
	Mashhad	Mech.	1		6,000			Environ. = 673,703,
		Cement	1	600	4,800			Social(× 1000) = 194, WPD_i = 15.2%
	Esfahan	Mech.	1			6000		
		Cement	1	2,100		2400		
	Shiraz	Mech.	1			600	5400	
22	Tehran	Mech	3	18,000				Profit = 34,486,271,
	Mashhad	Mech.	2		6,000			Environ. = 1,221,990,
	Esfahan	Mech.	2	3,600		8400		Social(× 1000) = 231, WPD_i = 10.8%
	Shiraz	Mech.	1			600	5400	

Ideal point: Profit = 34,637,459, Environnent = 476,567, Social(× 1000) = 281 (Mech. = mechanical pulverization, Cry. = cryogenic pulverization, Cement = fuel substitution in cement kiln).

5. Summary and conclusions

In this paper multi-objective programming model for multi-objective optimization of sustainable recovery network of scrap tires was presented. Regarding multi-dimensional concept of sustainability, the objectives were (1) maximization of total net profits of processing the EOL tires, (2) minimization of total environmental impact of all activities included in the EOL treatments and (3) maximization of social benefits. In doing so, environmental and social impact of each EOL option was quantified using Eco-indicator and AHP methodology, respectively. In addition, MOGA was applied to reach Pareto-optimal solutions for network configuration. Furthermore, weighted percent of deviation indicator was introduced to provide good insights into the quality of each Pareto-optimal solution. Results of example problem showed that there is tradeoff between objective functions in different network configurations. Profit objective function tends to utilize more from pulverization plants. With respect to environmental objective function fuel substitution is better option. Social objective tends to install more plants, especially in less developed locations. Finally, it can be concluded that WPD which incorporates the decision makers' preferences about objective functions, is a good measure to guide them in finding the preferred solutions regarding all objective functions simultaneously.

Appendix A. AHP and its implementation results

In AHP approach, the first step sets the problem as a hierarchy, where the topmost node is the overall objective of the decision, while subsequent nodes at lower levels consist of the criteria used in arriving at this decision. The second step requires pair-wise comparisons to be made between each pair of indicators (of the given level of the hierarchy). The comparisons are made by posing the question which of the two indicators i and j is more important with respect to the top node, respectively. The intensity of preference is expressed on a factor scale from 1 to 9. The value of 1 indicates equality between the two indicators while a preference of 9 indicates that one indicator is nine times the importance of the one to which it is being compared. These pair-wise comparisons result in a $(N \times N)$ (N is the number of indicators) positive reciprocal matrix A. A quick way to find the normalized weight of each indicator is normalizing each column in matrix A (dividing an indicator relative weight by the sum of relative weights in column), and then averaging the values across the rows; this average column is the normalized weight vector W containing weights of the indicators.

Table 12
Abbreviations.

Name	Abbreviation
Tehran	Teh.
Mashhad	Mas.
Esfahan	Esf.
Shiraz	Shi.
Mechanical pulverization	Mech.
Cryogenic pulverization	Cry.
Fuel substitution in cement kiln	Cem.

We define a code for each EOL option that has three sections. These sections denote the type of EOL, location of selected EOL plant and its capacity level, respectively. Abbreviations used in this coding are given in Table 12. For example 'Mech-Teh-1' means that a mechanical pulverization plant should be installed at first capacity level in Tehran.

Based on Expert Choice software (Expert Choice Inc., 2000), continuous scale from 1 to 12 has been chosen for pair-wise comparisons. This scale guarantees the higher precision of comparisons. Tables 13 and 14 illustrate two samples of comparison matrices. In these matrices, each number with its corresponding row and column shows the relative importance of the issue in the row compare to the issue in the column. Numbers lower than one present the lower importance of the row regarding the column. These compar-

Table 13
Comparisons of the relative importance of criteria with respect to social impact.

	Employment	Damage to worker	Product risk	Local development
Employment		7.00	7.00	5.00
Damage to worker			1.00	0.33
Product risk				0.20
Local development				

Table 14
Comparisons of the relative importance of EOLs with respect to local development.

	Mech-~~The~~-1	Mech-~~The~~-2	Mech-~~The~~-3	Cry-Teh	Cem-Teh	Mech-Mas-1	Mech-Mas-2	Mech-Mas-3	Cry-Mas	Cem-Mas	Mech-Esf-1	Mech-Esf-2	Mech-Esf-3	Cry-Esf	Cem-Esf	Mech-Shi-1	Mech-Shi-2	Mech-Shi-3	Cry-Shi	Cem-Shi
Mech-Teh-1		0.50	0.33	1.00	4.00	0.50	0.25	0.17	0.50	4.00	0.40	0.20	0.13	0.40	4.00	0.33	0.17	0.11	0.33	4.00
Mech-Teh-2			0.67	2.00	8.00	1.00	0.50	0.33	1.00	8.00	0.80	0.40	0.27	0.80	8.00	0.67	0.33	0.22	0.67	8.00
Mech-Teh-3				3.00	12.0	1.50	0.75	0.50	1.50	12.0	1.20	0.60	0.40	1.20	12.0	1.00	0.50	0.33	1.00	12.0
Cry-Teh					4.00	0.50	1.00	0.67	0.50	4.00	0.40	0.20	0.13	0.40	4.00	0.33	0.17	0.11	0.33	4.00
Cem-~~The~~						0.25	0.13	0.08	0.25	1.00	0.25	0.13	0.08	0.25	1.00	0.25	0.13	0.08	0.25	1.00
Mech-Mas-1							0.50	0.33	1.00	4.00	0.80	0.40	0.27	0.80	4.00	0.67	0.33	0.22	0.67	4.00
Mech-Mas-2								0.67	2.00	8.00	1.00	0.50	0.33	1.00	4.00	0.80	0.40	0.27	0.80	8.00
Mech-Mas-3									3.00	12.0	1.50	0.75	0.50	1.50	12.0	1.20	0.60	0.40	1.20	12.0
Cry-Mas										4.00	0.50	1.00	0.67	0.50	4.00	0.40	0.20	0.13	0.40	4.00
Cem-Mas											0.25	0.13	0.08	0.25	1.00	0.25	0.13	0.08	0.25	1.00
Mech-Esf-1												0.50	0.33	1.00	4.00	0.80	0.40	0.27	0.80	4.00
Mech-Esf-2													0.67	2.00	8.00	1.00	0.50	0.33	1.00	4.00
Mech-Esf-3														3.00	12.0	1.50	0.75	0.50	1.50	12.
Cry-Esf															4.00	0.50	1.00	0.67	0.50	4.00
Cem-Esf																0.25	0.13	0.08	0.25	1.00
Mech-Shi-1																	0.50	0.33	1.00	4.00
Mech-Shi-2																		0.67	2.00	8.00
Mech-Shi-3																			3.00	12.0
Cry-Shi																				4
Cem-Shi																				

Table 15
Pareto-optimal solutions of the example problem.

Solution number	Profit objective value	Environmental objective value	Social objective value	WPD (%)
1	34,637,459	754,794	221	8.0
2	34,448,730	789,948	243	8.4
3	34,088,730	1,804,308	262	17.8
4	32,263,320	4,208,838	280	24.3
5	34,178,730	1,550,718	260	12.3
6	34,358,730	1,043,538	252	13.6
7	34,576,271	968,400	229	13.2
8	34,268,730	1,297,128	258	18.1
9	34,547,459	1,008,384	230	14.8
10	33,483,090	2,644,788	277	29.8
11	24,656,840	555,551	222	18.9
12	29,910,867	673,703	194	15.2
13	31,588,886	5,112,127	281	26.8
14	29,699,498	586,127	238	18.5
15	29,888,227	550,973	216	16.0
16	25,359,663	476,567	209	83.8
17	25,442,867	515,249	187	70.4
18	33,663,090	2,137,608	266	104.3
19	34,545,143	882,906	222	48.3
20	29,609,498	839,717	244	42.8
21	34,457,459	1,261,974	236	20.5
22	34,486,271	1,221,990	231	10.8
23	32,778,960	3,621,948	279	25.4
24	34,455,143	1,136,496	232	24.0
25	33,573,090	2,391,198	275	37.6

isons have been made by individuals in the panel of experts. The average results have been given in this study.

Appendix B. Pareto-optimal solutions

Pareto-optimal solutions of the example problem have been given in Table 15.

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