Designing Sustainable Recovery Network for Waste from Electrical and Electronic Equipment (WEEE) using Genetic Algorithm

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Designing a sustainable recovery network for waste from electrical and electronic equipment using a genetic algorithm

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Abstract: In recent years, reverse logistic and closed-loop supply chain issues have became more important due to environmental, social and economic reasons. Product recovery which comprises recycling, remanufacturing, repairing and disposing requires an efficient reverse logistic network. Among used products, waste electrical and electronic equipment (WEEE) has become a major problem for developing countries due to its harmful effects. WEEE contains hazardous materials that may have an impact on both environment and human health if it is properly managed. On the contrary, valuable materials can be extracted if it is controlled properly. Therefore, decision makers should give consideration to design an efficient reverse logistic network to manage WEEE. In this paper, a mathematical model of two-stage RL network has been developed based on sustainable development objectives in which economic, environmental and social objectives are considered simultaneously. A multi objective genetic algorithm (MOGA) is developed to determine the best locations of collection centres and recycling plants. In result, the decision makers can make the trade-off between environmental issues and economic and social impacts. The proposed model is examined through a real case from Iran's WEEE current situation.

Keywords: reverse logistic network; multi objective genetic algorithm; MOGA; none dominated sorting genetic algorithm-II; NSGA-II; waste electrical and electronic equipment; WEEE; sustainable development.

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1 Introduction

As the global market continues to expand and innovation cycles become shorter, the change and replacement of equipment accelerates, making waste from electrical and electronic equipment (WEEE) one of the fast growing streams in the world with a growth rate of 3%–5% annually which is three times higher than the growth rate of the common trash (Rogers and Tibben-Lembke, 1999; Abu Bakar and Rahimifard, 2008).

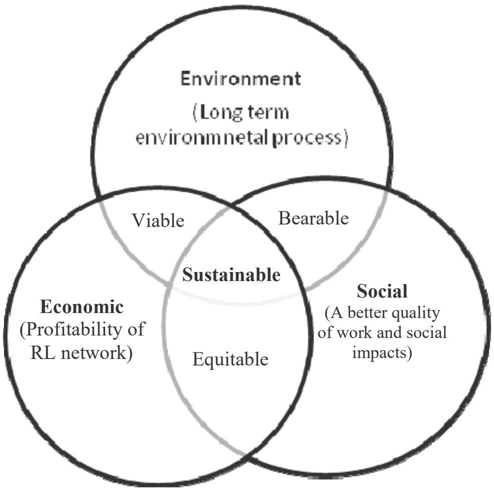
In last decade, the developing countries are facing huge challenges in the management of electronic waste and have urged to manage the WEEE stream (Carter and Rogers, 2011; Nnorom and Osibanjo, 2008). Therefore, they are seeking ways to optimise the reverse logistics network with respect to three objectives of sustainable development, namely: economic process, social development and environmental protection (Carter and Easton, 2011; Brundtland Commission, 1987; Carter and Rogers, 2008). Figure 1 shows the objectives of sustainable RL network.

Considering the fact that three mentioned objectives are almost conflicting and dependent, moving towards a sustainable RL network needs to be optimised while it fulfils all the three objectives at the same time in a way that:

- to achieve high and long-term economic viability
- to provide social progress meeting basic human needs and foundations of wellbeing
- to effectively protect the environment.

Currently, a great volume of WEEE is generated and goes directly to landfills without any treatment. In the last decade, the total amount of generated WEEE in Iran has increased due to increasing number of imported and used electrical products., that it has surpassed the GDP and population growth in 2010 (The World Bank, 2016).

Figure 1 The three pillars of sustainability



Source: Mangla et al. (2014)

For proper treatment of this rapid and uncontrollable rate of WEEE, the government of Iran has been urged to design an effective RL network (Taghipour et al., 2012). Main public concern is the lack of an efficient collection and recovery system. Currently there is no directive in place for safe collecting and disposing of e-wastes through authorised bodies such as the Environmental Protection Organization of Iran (IEPO). There is only one disposal site with the capacity of treating 0.8 tones WEEE per day that has been installed by the public sector (IEPO, 2016). Therefore the country has a great potential to install new facilities for treatment of electrical and electronic appliances at the EOL phase. For this reason, the aim of this paper is to develop a model to optimise the recycling network for all types of e-waste materials with respect to mentioned sustainable development objectives.

1.1 Literature review

In recent years various researchers have been paid attention to designate sustainable RL network (Jamshidi, 2011; Ilgin and Gupta, 2010; Ongondo et al., 2011; Chaabane et al., 2011). However, very few works have been published on the RL network design for all categorise of WEEE with respect to all three pillars of sustainable development at national level. The main reason of this literature review is to realise the major contribution of existing works in order to differentiate this research from those studies. The literatures were reviewed with following objectives in mind:

1 Which dimension of sustainability was considered?

2 Which modelling tool has been selected for solving the proposed problem?

3 Has the developed model been applied to investigate a RL network design at national or regional level?

4 What type of WEEE the research was aimed at?

5 What the outcome of the developed model?

According to the following areas the previous papers were reviewed and summarised in Table 1.

Table 1 Literature review on modelling sustainable nationwide WEEE network

Publication	*Sustainability dimension*	*Modelling tool*	*Case study*	*WEEE type*	*Research outputs*
Shih (2001)	Economical	MILP	Northern Taiwan	White goods, PC	Collection location, recovery location, resource allocations, material flows
Chang et al. (2006)	Economical	MILP	China (Jiangsu)	All type	Collection location, recovery location, material flows
Grunow and Gobbi (2009)	Economical	MILP	Denmark	All type	Collection location
Achillas et al. (2010a)	Economical	MILP	Greece	All type	Collection location, recovery location, material flows
Achillas et al. (2010b)	Economical, social, environmental	MCDM	Greece	All type	Recovery location
Xianfeng et al. (2010)	Economical	Simulation/ LP	Guangxi	All type	Collection location, recovery location, resource allocations, material flows
Bereketli et al. (2011)	Economical, social	LINMAP	Turkey	All type	Treatment strategy
Assavapokee and Wongthatsanekorn (2011)	Economical	MILP	USA (Texas)	TVs, CPU, CRT	CL, recovery location, resource allocations, material flows
Gomes et al. (2011)	Economical	MILP	Portugal	All type	Collection location, recovery location, material flows, Vehicle analysis
Roghanian and Pazhoheshfar (2014)	Economical, environmental	MILP	-	-	Collection location, recovery location, transportation roots

Shih (2001) developed a MILP model to design a RL network for recycling computers and home appliances in Taiwan. The proposed model attempted to minimise the total cost, which consists of transportation cost, operating cost, fixed cost for new facilities, final disposal and landfill cost, as well as the sale revenue of reclaimed materials. The model analysed different rates of take back and opening conditions. Chang et al. (2006) focused on logistics system for recycling WEEE in China. The MILP model was developed based on a capacitated warehouse location model. A Chinese province was examined as a case. Grunow and Gobbi (2009) provided an approach based on MILP modelling for optimising the location of WEEE collection centres in Denmark. The developed model aids the official agencies in assigning collective schemes to municipalities where consumers deliver the waste. Achillas et al. (2010a) presented a MILP model as a decision support tool for policy makers to optimise electrical and electronic products' reverse logistic networks in Greece. The developed model minimises total logistic costs including variable transportation costs and fixed and variable costs for the development of Intermediary Storages. In another research by Achillas et al. (2010b), the location of WEEE recovery facilities in Greece is investigated. The decision-making framework selects the best WEEE alternative locations employing multi-criteria methodology. Three objectives are considered in the developed model: social benefits (local and served population; unemployed population), economic objective (land value and financial status of local population) and accessibility criteria (location accessibility, distance from nearest port, distance from other existing facilities and the capital of the region). Xianfeng et al. (2010) proposed a reverse logistic network for modelling e-waste in Guangxi in China. The linear programming (LP) model was applied to determine the best location of WEEE. The objective function is minimisation of total transportation costs. The simulation model was used to analyse the results of the LP model. Bereketli et al. (2011) developed a fuzzy linear programming technique for multidimensional analysis of preference (LINMAP) model for evaluation and selection of a waste treatment strategy for WEEE in Turkey. Three treatment strategies (reusing and recycling, in-sourced disposal, out-sourced disposal) are selected based on eight criteria (Waste release period, First investment cost, Ratio of resource conservation, Stock cost, Process cost, Capacity need, Risk of damage for the nature and the human health, Convenience to the possessed technology). Assavapokee and Wongthatsanekorn (2011) proposed a solution methodology for designing the infrastructure of the reverse production in the state of Texas for TVs, CPUs and monitors waste. Regular collection site, hub collection site, regular processing site, hub processing site and a site for the temporary collection is determined by utilising the mixed integer linear programming (MILP) model. Gomes et al. (2011) proposed a generic MILP model to represent a Portuguese WEEE recovery network. In their model, the best locations for collection and sorting centres are chosen simultaneously. Roghanian and Pazhoheshfar (2014) developed a model for RL network under stochastic environment by genetic algorithm. They proposed a probabilistic MILP for multi-product, multi-stage RL network problem for the return products to determine the subsets of disassembly and processing centres and also the transportation strategy that will satisfy demand.

Literature reviews into RL network design are mostly divided to two categories: minimising costs (or maximising profits) and minimising environmental impact. Few researches have been done in field of integrating these two approaches.

The social side of sustainability in RL networks have always been ignored in literature (Bloemhof Ruwaard et al., 2004). As was studied in the literature, modelling a RL network for WEEE with respect to all objectives of sustainable development is a relatively new concept. Major findings of our literature study and contributions and objectives of this paper are summarised as follows:

- Designing sustainable RL network: In most recent works, the location of collection and disposal sites was optimised based on the total costs of the RL network while other sustainable development objectives were not considered. In the proposed model, decisions for all categories of WEEE in Iran will be made with respect to social, environmental and economic objectives simultaneously. However, the objectives of the presented paper are modelling the overall process of RL network.
- In this paper, mathematical model of two-stage RL network has been developed based on sustainable development objectives in which economic, environmental and social objectives are considered simultaneously. A multi objective genetic algorithm (MOGA) is developed to determine the best locations of collection centres and recycling plants. In result, the decision makers can make the trade-off between environmental issues and economic and social impacts. The none dominated sorting genetic algorithm-II (NSGA-II) algorithm will be applied and adapted for optimising the proposed problem.
- Case study – the national WEEE RL network: A case study for WEEE RL in Iran will be applied and results will be discussed. The proposed model will be examined through an example by using a real set of data representing WEEE situation in Iran.

2 Method

The objective of this paper is to design a sustainable recovery network in which economic, environmental and social impacts are balanced. Previous studies were investigated to find indicators. Analytical hierarchy process (AHP) has been utilised to calculate social impacts. Next in this research, a three-objective mathematical programming model has been developed to maximise economic and social Benefits and minimise negative environmental impacts simultaneously. A case study for WEEE RL in Iran has been considered and MOGA with NSGA-II has been applied to find the Pareto-optimal solutions.

2.1 Conceptual model

To solve the proposed problem, MOGA with NSGA-II optimisation method was applied. With this technique, a RL model including all the associated uncertainties within the proposed network is developed. Figure 2 shows the main criteria regarding to sustainable three pillars of the developed model. The objectives of the developed model are as follow:

2.1.1 Cost objectives

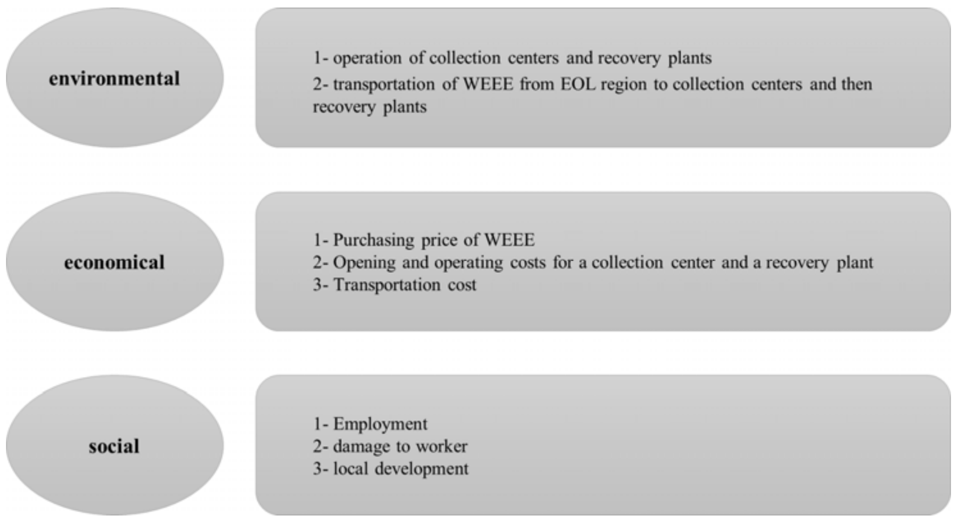
a To sell price of the recovered materials in collection centres or recovery plants that are sold in the market.

b To purchase price of WEEE from consumers.

c To open and operating costs for a collection centre and a recovery plant.

d To transport cost from EOL region to collection centres and then to recovery plants.

Figure 2 The main criteria regarding to sustainable three pillars of the developed model



21.2 Environmental objectives

a Environmental impacts relating to operation of collection centres and recovery plants.

b Environmental impacts relating to transportation of WEEE from EOL region to collection centres and then from collection centres to recovery plants.

2.1.3 Social objectives

Social impacts (employment, damage to worker, local development) of collection centres and recovery plants.

Therefore, as it is shown, the costs, environmental and social impacts of dismantling, remanufacturing and recovering activities are out of scope of this research.

In order to design a sustainable RL network, all categories of WEEE are listed in Table 2. These categories are based on appropriate end of life existing treatment technologies in Iran and a report from real case study by Huisman et al. (2008). Furthermore, in this paper all of WEEE which have not been collected since 2011, have been sent to landfills or collected through illegal electronic market, so they are not considered as input data to the developed model.

Table 2 WEEE categories

ID	*WEEE category*
1	Large household appliances, automatic dispensers
2	Cooling and freezing
3	Large household appliances (smaller items)
4	Small household appliances, lighting equipment, luminaries and 'domestic' medical devices, monitoring and control instruments

Table 2 WEEE categories (continued)

ID	*WEEE category*
5	IT and telecom except CRT's
6	CRT monitors
7	LCD monitors
8	Consumer electronics except CRTs
9	CRT TVs
10	Flat panel TVs
11	Lighting equipment, lamps
12	Electrical and electronic tools
13	Toys, leisure and sports equipment
14	Modelling devices (merged in category 4)
15	Monitoring and control Instruments (merged in category 4)
16	Automatic dispensers (merged in category 1)

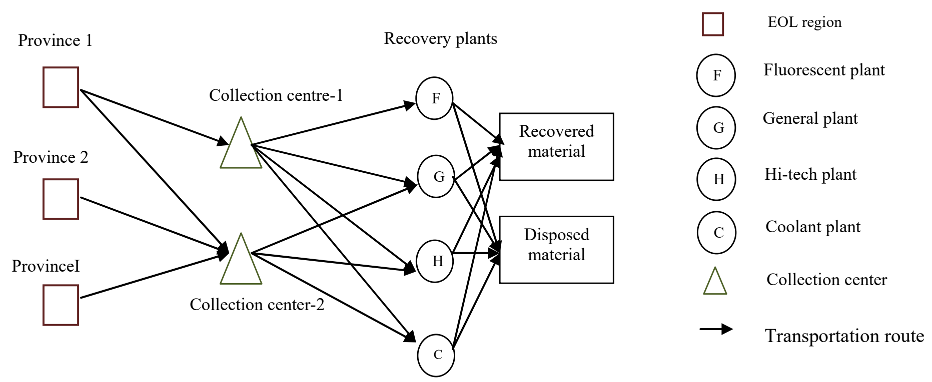
Source: Huisman et al. (2008)

In order to design the reverse logistic network, it is essential to identify all the economic, environmental and social impacts of operations take place in WEEE recovery network for all WEEE categories described in Table 2. Therefore, four groups of activities which have influence over WEEE recovery network are determined (Fleischmann et al., 2003):

- Collection: to collect WEEE through regions safely and completely.
- Transportation: convey WEEE products to the collection centres and pre-treated products to recycle facilities.
- Pre-treatment and separation: only some WEEE groups are entirely free of hazardous materials. The others should be pretreated in such ways that is appropriate to be fed into recycling plants.
- Recycling treatment: the end node of WEEE recovery network that comprises different plants for recycling and treatment of different EOL products.

According to these activities, the WEEE reverse logistic network presented in Figure 3.

Figure 3 The proposed WEEE recovery network (see online version for colours)



In the collection centres, WEEE should be collected separately and properly treated to segregate hazardous materials which cannot be treated using installed technologies in the plants. Running the collection centre in a higher capacity level needs higher constant costs. Later, the generated materials are transported to the recovery plants. Four types of recovery plants for treatment of different EOL electrical and electronic equipment have been considered in the proposed model:

- fluorescent recycling plants
- general equipment treatment plants
- CRT and LCD hi-tech plants
- coolant and freezer treatment plants.

Each plant can be established in potential locations and have predefined capacity. The presented model also has assumed an evolutionary PCB-PWB flexible plant which is installed beside each of the proposed capable plants except in fluorescent recycling facility to dispose the circuit boards of WEEE groups completely.

The EOL regions (provinces) are assumed to be located in the central city of each region as they are considered to be more suitable for installing treatment plants in terms of technological advantages and high transportation infrastructures. In the developed model, 30 possible alternative collection centres (number of provinces in Iran) are defined. Therefore, the location and type of recycling plants and shipment quantity of WEEE pre-treated products should be found as well as location of collection centres and collected WEEE through EOL regions.

In the next section, the methodology for modelling and optimising the WEEE reverse logistic network with respect to economic, environmental and social objectives is described.

2.2 Mathematical model

According to mentioned sustainable development objectives and conceptual model, economic, environmental and social objectives are as follows:

2.2.1 Economic objective function

End of electrical and electronic equipment should no longer be considered as wastes are sent to landfills or incineration facilities. Processing WEEE at least produces valuable second hand materials such as Cu, Pd, Au, etc., that have customers all over the world with international prices. Therefore, economic benefit of a reverse logistic network is one of the most crucial aspects of WEEE network. However, to achieve such benefits first it should deal with the design and planning of a recovery network which needs expenditures. These expenditures include capital cost of installing and operating infrastructures, recycling facilities, collection centres and the cost of transportation between different nodes in RL network. In the developed model, profit objective function for RL network is considered economic parameters to maximise the total profit of recycling and treating waste electrical and electronic device.

2.2.2 Social objective function

As mentioned in literature review section, most previous models consider only economic and environmental aspects of sustainable development, but very few of them consider social benefits of reverse logistic network (Morrissey and Browne, 2004). In this paper, the issues of logistics social responsibility and corporate social responsibility (Carter and Jennings, 2002; Vargas, 2002; Dehghanian and Mansour, 2009), World Development indicators (The World Bank, 2016) and social indicators for sustainable projects and technology life cycle management in the process industry (Carter and Jennings, 2002) are presented to the panel of experts in department of deputy strategic planning and control. The framework of social sustainability criteria was identified and introduced in Table 3.

Table 3 Social issues

Row	*Criteria*	*Description*
1	Employment	Different EOL options can create number of employment opportunities. Decrease in unemployment rate causes community development which is an important issue in governmental social responsibility.
2	Damage to worker	Different EOL recyclers may be exposed to hazardous environment for workers based on hazardous substances which are contained in WEEE products. Environmental impact of potential locations on worker health, mainly air pollution can be threatening to the labour's health.
3	Local development	Installing facilities in less developed areas causes community development which is an important issue in governmental social responsibility. Provinces which attract more investors have more chance to install new plants and factories.

Some factors in Table 3 are related to the geographical location of recovery plants, some of them are related to recycling methods and product health hazards, and some are affected by both.

Through applying AHP approach, the problem sets as a hierarchy, where the topmost node is the overall social indicator, while subsequent nodes at lower levels consist of the criteria which are used for building overall social indicator.

2.2.3 Environmental objective function

Many papers have studied environmental impacts of WEEE recovery networks (Huisman et al., 2008). Wäger et al. (2011) presented the results of a combined material flow analysis and life cycle assessment (LCA) study and also calculated overall environmental impacts of collection, preposition and end-processing for the existing WEEE collection and recovery system as well as of incineration and land filling scenarios. In this paper, the analysis on environmental impacts is based on treating 1 ton (1,000 kg) of different EOL products. The developed model used Eco-indicator 99 methodology (Consultants, 2000) to assess the relative environmental impacts. However calculating the exact impact of each EOL options is not the purpose of this paper and approximately reliable and acceptable impacts are considered.

In terms of the notation which is defined in the Appendix, the problem can be formulated as follows:

$$\begin{aligned} Max\ Z_1 = & \sum_{q=1}^{Q}\sum_{r=1}^{R}\sum_{j=1}^{J}\sum_{s=1}^{S}\sum_{l=1}^{L} Y_{jslq} W_q O_r B_{rq} - \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{q=1}^{Q} X_{ijq} P_q \\ & - \sum_{j=1}^{J}\sum_{h=1}^{H} C_j^h e_j^h V_j^h - \sum_{s=1}^{S}\sum_{h=1}^{H}\sum_{l=1}^{L} C_s^h e_s^h V_{sl}^h \\ & - C^T \left[\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{q=1}^{Q} X_{ijq} d_{1ij} + \sum_{j=1}^{J}\sum_{s=1}^{S}\sum_{q=1}^{Q} Y_{jslq} d_{2jl} \right] \end{aligned} \tag{1}$$

$$\begin{aligned} Max\ Z_2 = & \sum_{j=1}^{J}\sum_{h=1}^{H} \left(W_{EM} EM_j^h + W_{DTW} DTW_j^h + W_{NLD} NLD_j^h \right) V_j^h \\ & + \sum_{s=1}^{S}\sum_{l=1}^{L}\sum_{h=1}^{H} \left(W_{EM} EM_{sl}^h + W_{DTW} DTW_h^h + W_{NLD} NLD_{sl}^h \right) V_{sl}^h \end{aligned} \tag{2}$$

$$Min\ Z_3 = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{q=1}^{Q} X_{ijq} d_{1ij} EL^T + \sum_{j=1}^{J}\sum_{s=1}^{S}\sum_{l=1}^{L} Y_{jslq} \left(EL_s + d_{2jl} EL^T \right) \tag{3}$$

Constraints:

$$\sum_{i=1}^{I}\sum_{q=1}^{Q} X_{ijq} \le e_j^h V_j^h; \quad \forall j, h \tag{4}$$

$$\sum_{j=1}^{J}\sum_{q=1}^{Q} Y_{jslq} \le e_s^h V_{sl}^h; \quad \forall s, l, h \tag{5}$$

$$\sum_{j=1}^{J}\sum_{l=1}^{L} Y_{jslq} \le e_s^h V_{sq}; \quad \forall s, q \tag{6}$$

$$\sum_{s=1}^{S}\sum_{l=1}^{L} Y_{jslq} \le \sum_{i=1}^{I} X_{ijq}; \quad \forall j, q \tag{7}$$

$$\sum_{h=1}^{H} V_j^h \le 1; \quad \forall j \tag{8}$$

$$\sum_{h=1}^{H} V_{sl}^h \le 1; \quad \forall s, l \tag{9}$$

$$V_{sl}^h \in (0, 1) \tag{10}$$

$$V_j^h \in (0, 1) \tag{11}$$

Equation (1) represents the economic impact of RL. The first and second term in equation (1) correspond to sell price of recovered material in collection centres and recovery plant. The third term deals with the purchase price of WEEE. The fourth and fifth term represents opening and operating cost for collection centre and recovery plant, respectively. The last two terms in equation (1) represent transportation cost from EOL region to collection centres and then to recovery plants. Equation (2) represents social impacts of network. The first term in equation (2) corresponds to social impact of collection centres with respect to indicators which summarised in Table 3. Also, the second term represents social impact of recovery plant with respect to mentioned indicators. Equation (3) minimises total environmental impacts of network. The first term of equation (3) corresponds to environmental impact of transportation of WEEE to collection centres. The second term represents environmental impacts for transporting from collection centre to recovery plant and then recovering the materials.

Constraints (4) and (5) correspond to capacity restriction of the collection centres and recovery plants. Constraint (6) represents the restriction of recovery plant type. Constraints (7) correspond to restriction of RL flow in the network. Constraints (8) and (9) denote that a collection centre and recovery plant at each location can be assigned at most one capacity level. Constraints (10) and (11) impose the integrality restrictions on the binary variables.

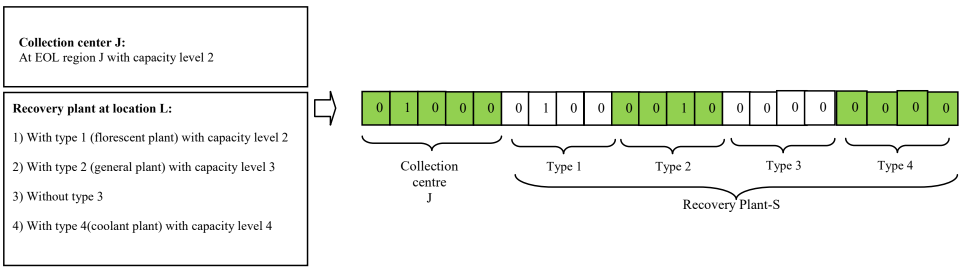
2.3 *Solution method*

The research problem is a multi-objective MILP model. The developed mathematical model is a general variant of the location-allocation model and hence is an NP-hard problem and does not permit for developing polynomial time exact algorithms (Jayaraman et al., 2003). Therefore, for solving the developed model NSGA-II has been applied proposed by Deb et al. (2002) to find the Pareto-optimal frontier same as many related problems in the field of EOL context. The algorithm is efficient in approximating the Pareto frontier results and it is applied widely to solve multi-objective problems (Jones et al., 2002). In addition, this algorithm is used with the same size in Dehghanian and Mansour (2009) work. The following steps describe how the multi-objective genetic algorithm has been implemented for our problem in detail.

2.3.1 *Step 1: Representation and initial population generation*

Chromosome representation for the proposed problem is shown in Figure 4.

Figure 4 The chromosome representation for the proposed problem (see online version for colours)

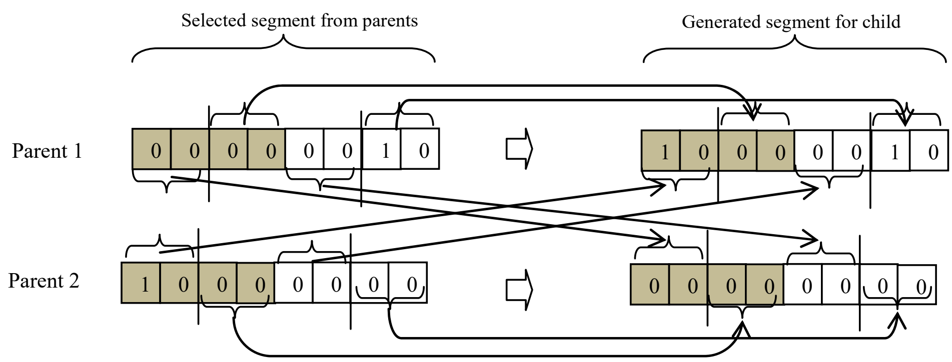


Each location for collection centres represents with four binary genes. Each gene represents one the collection centre capacity where 1 denotes the location considered for the construction of collection centre with capacity level H and 0 addresses otherwise. Same as collection centres, 16 gens are considered for each recovery plants. Each gene represents the type and capacity of selected recovery plants.

2.3.2 Step 2: Crossover

The segment-based crossover is applied to generate new chromosomes from the population (Ahluwalia and Nema, 2007). In the developed model, 30 segments considered for collection centre and 30 * 4 segments represents the recovery plants. Each segment of collection centres and recovery plants is randomly selected with equal chance among the segments of parents. '0' means that selected segments of parents will not transfer their genetic materials to each other while '1' means differently. Then, the two-point crossover is selected for generating new chromosomes. Figure 5 represents the crossover for the proposed problem

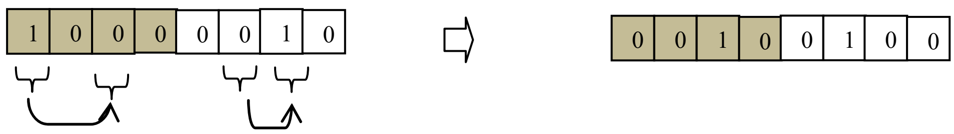
Figure 5 The crossover operation (see online version for colours)



2.3.3 Step 3: Mutation

Similar to crossover operator, segment-based mutation has been applied based on the selected segment. This operator selects two genes from the selected segment and exchanges their places (Figure 6).

Figure 6 The mutation operation (see online version for colours)



2.3.4 Step 4: Fitness function

Each chromosome has three fitness values with respect to social and economic and environmental objective functions. Each chromosome specifies the location and capacity of collection centres and location, type and capacity of recovery plants which can be transformed to profit, environmental and social objective functions. Each solution is compared with a set of non-dominated solutions and optimised solution is selected.

2.3.5 Step 5: Chromosome selection

Initial population is randomly generated and Pareto-optimal frontier is created by non-dominated sorting of results on the initial population. Non-dominated sorting creates a number of fronts of non-dominated solutions in which the first front includes solutions that cannot be dominated by other solutions. To build a new population, the algorithm starts from the first front and selects solutions until the number of selected solutions equals to the population size. If the number of solutions in the first front is less than the population size, the algorithm goes through the other fronts, respectively, to choose new solutions (Deb et al., 2002).

2.3.6 Step 6: Terminating the algorithm

Termination condition limits the total number of generations. In this study, the algorithm will be terminated if the total number of generation reaches to a certain predefined number.

3 Result and discussion

3.1 Illustrative case from IRAN

The applicability of the developed model is illustrated by a real-life case for the development of the reverse logistic network of WEEE in Iran.

Before implementing the model, some assumptions must be mentioned:

- WEEE generation data: the data from 1995 through end of 2010 was provided by Customs Administration of Iran (IRICA, 2016) and Statistical Centre of Iran (SCI, 2016). WEEE data only in seven categories are gathered by Taghipour et al. (2012) during 2005–2010. Therefore, WEEE data for all type of WEEE is obtained from mentioned organisations. To obtain the collaboration and support of the IRICA and SCI, a formal letter was sent to each office and after interviewing with the relevant authority in the mentioned governmental organisations, the required data was gathered. Moreover, the data was validated by the research was done by Taghipour et al. (2012) in seven categories of WEEE between 2005 through 2010. Then, these data was applied to determine the probabilistic distribution functions for WEEE generation in Iran.
- The probability function of material type, r, which can be recovered form WEEE type q was based on dismantler's assessments.

- EOL regions: Each province has the capability of having its own collection centre or shipping the waste to other provinces.
- Collection centres: The suggested capacities are 10,000, 15,000, 20,000, 40,000 and 70,000 ton/year. These capacities can be changed as input parameters in the model without changing the model.
- Recovery plant: WEEE in each collection centre transported to provinces which are the potential sites for establishment of recovery plant with four different capacities (2,000, 8,000, 12,000 and 20,000). Each recovery plant is assumed to work 8 hour per day shift and 250 operating days per year.
- Landfill cost: The landfill cost is added to fixed cost for both collection centre and recovery plant.
- Computing social objective: Based on indicators which are defined in Table 4, the AHP model was applied. Table 4 gives the relative weight of social indicators.
- Transportation costs: Is calculated based on shipping cost of 1 tons of scrap WEEE per kilometre. The types and capacity of vehicles being used were not modelled in the proposed problem.
- The model was planned for ten years.
- Other input parameters based on dismantling experts are summarised in Table 5.

Table 4 Relative weight of social criteria

Criteria	*Normalise weight*
Employment	58.4%
Damage to workers	28.2%
National and local development	13.4%

Table 5 Other model input parameters

Plant type	*Opening and operating cost per year for minimum capacity (*10,000 rials)*	*Profit of 1 ton of output (*10,000 rials)*	*Environmental impact of 1 ton of processing (Pt)*
Fluorescent recycling	1,712,572	654	21
General equipment	1,543,110	1,421	32
Hi-tech	1,424,654	1,231	38
Coolant and freezer treatment	2,847,754	1,137	17

3.2 Results

NSGA-II algorithm (as described earlier) is applied to solve this problem. The proposed GA algorithm has been coded in MATLAB 7.04 and executed on a computer with 2.8 GHz of CPU and 2,048 MB RAM. Crossover rate, mutation rate and population size set to 0.8, 0.2 and 400 respectively with respect to test experiments. The algorithm was stopped after 3,000 generations. Pareto-optimal solutions of given example are depicted in Table 6. The solution method found 25 different solutions for network configuration.

Table 6 The optimal location of recovery plants along their capacities (ton/year)

City	*Plant type*			
	F	*G*	*H*	*C*
Tehran	2,000	20,000	20,000	20,000
Esfahan	-	12,000	8,000	-
Shiraz	-	8,000	-	8,000
Mashhad	2,000	12,000	8,000	-
Tabriz	2,000	18,000	12,000	8,000
Hamadan	-	12,000	12,000	8,000
Sari	-	12,000	8,000	-
Yazd	2,000	20,000	12,000	8,000

Table 7 The optimal location of collection centres along their capacities (ton/year)

City	*Collection centre capacity*
Tehran	60,000
Esfahan	25,000
Shiraz	15,000
Mashhad	25,000
Tabriz	45,000
Hamedan	15,000
Sari	15,000
Yazd	25,000
Kerman	35,000
Shahrkord	15,000
Zanjan	15,000
Golestan	15,000

Transportation cost accounts for 56% of total cost. Collection centre and recovery plant cost are 18% and 26% of total cost respectively.

4 Conclusions

The management of WEEE is becoming an important issue and has become a huge challenge for governments of developed and developing countries. Therefore the developed model which considers all aspects of sustainability could be considered as an important tool for efficient management of generated WEEE. The developed model maximises the total net profits and social benefits of processing the WEEE stream as well as minimises the total environmental impacts of WEEE reverse logistics network. The environmental impacts of each network configuration were quantified by applying Eco-indicator. Moreover, social impact of each decision was quantified by AHP methodology. NSGA-II algorithm was applied for optimising the developed model and results were analysed. The proposed model is a wide nation model and was examined through an example by using WEEE data in Iran. The owner of reverse supply chain's processes in Iran is waste management organisation (TWMO, 2016). This model helps the organisation to determine the best locations of collection centres and capacity of recycling plants. Gathering regional data was the complex 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 (Taghipour et al., 2012). Future research directions that can be derived from the work include incorporating and quantifying other social issues such as Public health and safety in to the model as well. In addition, in the presented work, a simulated optimisation model is developed for modelling the proposed problem. Game theory is another method that can be applied. The consumer and the government can be regarded as two players in the game model and their preferences can be modelled using game theory approach.

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Appendix

Indices and parameters

I	Index set of regions where $i = 1, \ldots, I$
J	Index set of collection centres where $j = 1, \ldots, J$
L	Index set of potential plant centres where $l = 1, \ldots, L$
Q	WEEE type where $q = 1, \ldots Q$
S	Type of recycler $s = 1, \ldots, S$
H	Index set of capacity levels available to the potential facilities
W_q	Percent weight of WEEE type q in all type of WEEE
C_S^H	Fixed cost per unit of time for opening and operating plant type s with capacity h
C_J^H	Fixed cost per unit of time for opening and operating collection with capacity h
e_S^H	Capacity with level h for the potential plant type s
e_j^H	Capacity with level h for the potential collection centres at site j
d_1IJ	Distance from region i to collection centre at site j
d_2IJ	Distance from collection centre j to potential plant l
B_{rq}	Fraction of WEEE type q with material type r
C^T	Cost of shipping 1 tons of WEEE per kilometer
O_r	Sale price of material r

Indices and parameters (continued)

EL_s	Environmental impact of processing 1 tons of WEEE using plant s
P_q	Average buying price of WEEE type q
EL^T	Environmental impact of shipping 1 tons of WEEE
W_{EM}	Normalised weight of employment
W_{DTW}	Normalised weight of damage to workers
W_{NLD}	Normalised weight of national and local development
EM_{Sl}^h	Employment score of potential plant s at site l with capacity h
DTW_{sl}^h	Damage to workers score of potential plant s at site l with capacity h
NLD_{sl}^h	Local development score of potential plant s at site l with capacity h
EM_j^h	Employment score of potential collection centre j with capacity h
DTW_j^h	Damage to workers score of potential collection centre j with capacity h
NLD_j^h	National and local development score of potential collection centre j with capacity h

Variables

X_{ijq}	Quantity of shipments of product q from region i to collection centre j
Y_{jslq}	Quantity of shipments of product q from collection centre j to recycler type s at site l
V_{sq}	1 if type q can be processed with plant s, otherwise 0
V_{sl}^h	1 if plant s with capacity level h located at site l, otherwise 0
V_j^h	1 if collection centre j with capacity level h located at site j, otherwise 0