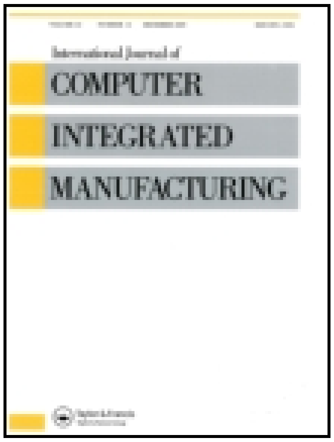

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Simulation-based optimisation of a sustainable recovery network for Waste from Electrical and Electronic Equipment (WEEE)

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In recent years, developing countries are facing huge challenges in the management of 'Waste from Electrical and Electronic Equipment' (WEEE). Waste from electrical and electronic equipment contains hazardous materials that may have an impact on human environment and health if not properly managed. Therefore, governments should be concerned and be seeking ways to design the recovery and disposal networks to manage WEEE waste treatment strategies. The objective of this paper is to design a country level WEEE recovery network based on sustainable development in which economic, environmental and social issues are considered. A simulation optimisation model is developed to determine the best locations for the collection centres and also recycling plants for managing total WEEE in Iran, so that the government can simultaneously perform the trade-off between environmental issues and economical and social impacts. The proposed model was examined through an illustrative case study from Iran's current WEEE situation.

Keywords: WEEE; simulation optimisation; reverse logistic; sustainability

1. Introduction

Waste from electrical and electronic equipment (WEEE) is one of the fastest growing waste streams in the world with a growth rate of 3–5% annually (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 are urged to manage the WEEE stream (Nnorom and Osibanjo 2008, Ongondo *et al*. 2011). Therefore, they are seeking ways to optimise the reverse logistics (RL) network with respect to three objectives of sustainable development, namely: economic development, social development and environmental protection (Bruntland 1987, Cowell and Parkinson 2002). Considering that the three mentioned objectives are almost conflicting and dependent, therefore moving towards a sustainable development needs to be optimised and is also required to meet all the three related objectives simultaneously in a way that:

- Achieves high and long-term economic viability.
- Provides social progress which recognises the needs of everyone.
- To effectively protect the environment.

Today, some of the governments in many countries are financially and organisationally responsible for the take-back of the products when they reach the end of their life cycle. These issues rise up as the term 'national RL network design' (Mansour and Zarei 2008). Literature reviews into RL network design are mostly divided in two categories: minimising costs (or maximising profits) and minimising environmental impact. There is little research done integrating these two approaches. The social side of sustainability in RL networks have always been ignored in literature (Bloemhof Ruwaard *et al*. 2004).

Currently, a great volume of WEEE is generated that goes directly to landfills without any treatment. Decisions for achieving sustainability in a recovery network of WEEE are directly dependent on the total amount of WEEE generated.

In the last decade, the total amount of WEEE generated in Iran has increased due to increasing numbers of imported and used electrical products. Figure 1 illustrates the growth of WEEE generation in Iran, such that it has surpassed the GDP and population growth in 2010 (World Bank 2011).

For proper treatment of this rapid and uncontrollable rate of WEEE growth, the government of Iran has been urged to design an effective RL network (Taghipour *et al*. 2011). The main public concern is the lack of an efficient collection and recovery system. Currently, there is no directive in place for safe collection and disposal of e-wastes through authorised bodies such as the Environmental Protection

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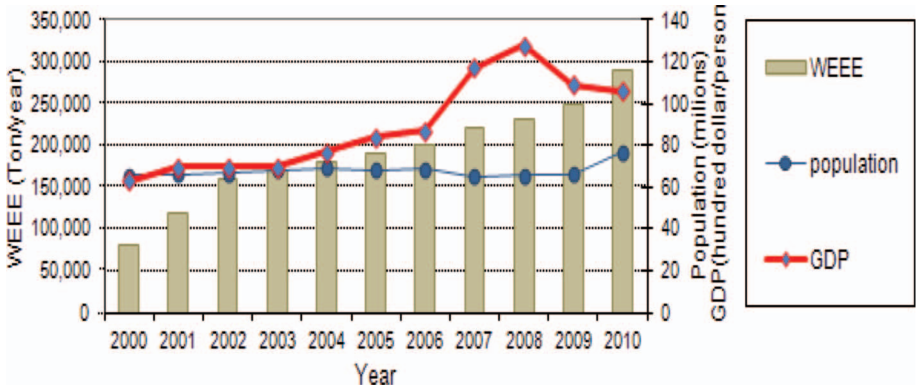

Figure 1. WEEE, population and GDP from 2000 until 2010.

Organisation (EPO) of Iran. There is only one disposal site with the capacity of treating 0.8 tonnes of WEEE per day that has been installed by the public sector (EPO 2011). Therefore, the country has a great potential to install new facilities for treatment of electrical and electronic appliances at the End of Life (EOL) phase.

This paper is organised as follows: in the next section the published works on modelling RL network at national level for different countries are reviewed. Section 3 introduces modelling the problem. Section 4 deals with the design of an optimisation procedure while Section 5 describes the case study relating to the proposed problem. Section 6 deals with discussion of the results and finally, Section 7 is devoted to conclusions and recommendations for future studies.

2. Literature review

In recent years, various researchers have been paying attention to designing sustainable RL network (Ilgin and Gupta 2010, Jamshidi 2011, Ongondo *et al.* 2011). However, very few works have been published on the RL network design for all categories of WEEE with respect to all three pillars of sustainable development at national level. In the WEEE literature, only one research has been conducted on the WEEE management in Iran. This research summarised data for eight categories of WEEE and has studied the extended of producer responsibility (EPR) among Iranian organisations (Taghipour *et al.* 2011).

The main reason of this literature review is to realise the major contributions 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 are the outcomes of the developed model?

The outcome of the reviewed literature is summarised in Table 1.

Vuk and Kozelj (1991) applied the PROMETHEE methodology and the geometrical representation of multi-criteria analysis to select locations for disposal sites of municipal wastes in Slovenia. Shih (2001) developed a mixed integer linear programming (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, operating cost and fixed cost for new recovery plants, final disposal and landfill cost, as well as the sales revenue for reclaimed materials. The model has analysed different rates of take back. 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 and a Chinese province was investigated as a case study. Kara *et al.* (2003, 2007) presented a simulation model to calculate collection costs for EOL appliances in the Sidney Metropolitan area. Queiruga *et al.* (2008) investigated a method to select the best location for WEEE recycling plants in Spain. This study was conducted by ECOLEC foundation that has been setup by the business associations that represent the manufacturing sector and importers of electrical and electronic appliances. The authors have defined this as a multi-criteria decision making (MCDM) problem, where three major criteria were chosen: economic, infrastructure and legal. The primary objective of the study was not to propose an optimal structure in terms of recycling plants, but rather to propose a set of good alternatives for potential collection locations. Rousis

Table 1. Literature review on modelling sustainable nationwide WEEE network.

Publication	Sustainability dimension	Modelling tool	Case study	WEEE type	Research outputs
Vuk *et al.* (1991)	Economical, environmental	MCDM	Slovenia	White goods	Vehicle analysis
Shih (2001)	Economical	MILP	Northern Taiwan	White goods, PC	Collection and recovery locations, resource allocations, material flows
Kara *et al.* (2003)	Economical	Simulation	Sidney	White goods	Vehicle analysis
Chang *et al.* (2006)	Economical	MILP	China (Jiangsu)	All type	Collection and recovery locations, Material flows
Kara *et al.* (2007)	Economical	Simulation	Sidney	White goods	Vehicle analysis
Queiruga *et al.* (2008)	Economical, infrastructure, legal	MCDM	Spain	All type	Recovery locations
Rousis *et al.* (2008)	Economical, social, environmental, technical	MCDM	Cyprus	All type	Recovery locations
Guerra *et al.* (2008)	Economical	Simulation	Southern Italy	White goods	Vehicle analysis
Grunow *et al.* (2009)	Economical	MILP	Denmark	All type	Collection locations
Gamberini *et al.* (2010)	Economical, environmental	Simulation	North of Italy	All type	Resource allocations
Achillas *et al.* (2010 a)	Economical	MILP	Greece	All type	Collection and recovery locations, Material flows
Achillas *et al.* (2010 b)	Economical, social, environmental	MCDM	Greece	All type	Recovery locations
Xianfeng *et al.* (2010)	Economical	Simulation/LP	Guangxi	All type	Collection and recovery locations, resource allocations, material flows
Bereketli *et al.* (2011)	Economical, social	LINMAP	Turkey	All type	Treatment strategy
Assavapokee *et al.* (2011)	Economical	MILP	USA (Texas)	TVs, CPU, CRT	CL, recovery locations, resource allocations, material flows
Gomes *et al.* (2011)	Economical	MILP	Portugal	All type	Collection and recovery locations, material flows, vehicle analysis

et al. (2008) applied the MCDM method for the selection of the best WEEE treatment scenario based on sustainable development objectives in Cyprus. Twelve treatment strategies were selected based on economical, social, environmental and technical criteria. Guerra *et al.* (2008) developed a logical model to present the WEEE (only White goods) distribution flows in southern Italy (nine provinces). In the developed model, the number of vehicles for collecting WEEE was analysed by utilising simulation modelling. 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 governmental agency in the assignment of collective schemes to municipalities where consumers deliver the waste. Gamberini *et al.* (2010) developed a generic model to optimise the number of required vehicles, maximum saturation of vehicles' capacity and the utilisation of vehicles' working times for handling WEEE with respect to environmental and economical objectives in Northern Italy. The environmental impact was quantified by life cycle assessment (LCA) method and the results were applied in a simulation model. Achillas *et al.* (2010a) presented a MILP model as a decision support tool for policy makers to optimise the electrical and electronic products' RL network in Greece. The developed model minimises total logistics costs including variable transportation costs and fixed and variable costs for the establishment of intermediary facilities. In another research by Achillas *et al.* (2010b), the location of WEEE recovery facilities in Greece was investigated. The multi-criteria methodology was adopted in the decision-making framework for the selection of the best WEEE alternative collection locations. Three objectives were considered in the developed model namely: social benefits (local development; unemployed population), economic (land value and financial status of local population) and accessibility criteria (location accessibility and distances from: the nearest port, the capital of the region, and other existing facilities). Xianfeng *et al.* (2010) proposed a RL network for modelling e-waste in Guangxi province in China. The linear programming (LP) model was applied to determine the best collection centres for WEEE. The objective function was the minimisation of the total transportation costs. Then the simulation model was used to analyse the results of the LP model. Bereketli *et al.* (2011) developed a fuzzy-based linear programming technique for evaluation and selection of a waste treatment strategy for WEEE in Turkey. Three different treatment strategies (reuse and recycling, in-sourced and out-sourced disposal) were selected based on eight criteria (waste release period, first investment cost, ratio of resource conservation, stock cost, process cost, capacity need, risk of possible damage to the nature and the human health, convenience of using the technology for worker). 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 the site for the temporary collection were determined by utilising the MILP model. Gomes *et al.* (2011) proposed a generic MILP model to represent the Portuguese WEEE recovery network. In their model, the best locations for collection and sorting centres are chosen simultaneously.

Further characteristics of reviewed literatures are summarised and compared in Table 1.

3. Objectives and contributions

As shown in the literature review, modelling a nation-wide RL network for WEEE with respect to three pillars of sustainable development is a relatively new concept.

According to the gap analysis of recent literature conducted by the authors, the major findings of the studied literature and contributions and objectives of this work are summarised as follows:

(1) *Designing sustainable RL network*: In most recent works, the location of collection and disposal sites were 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 economical objectives simultaneously. However, the objectives of the presented paper are modelling the overall process of RL network as follows:
   - (i) Cost objective:
     - (a) Selling price of the recovered materials in collection centres or recovery plants that are sold in the market
     - (b) Purchasing price of WEEE from consumers
     - (c) Opening and operating costs for a collection centre and a recovery plant
     - (d) Transportation cost from EOL region to collection centres and then to recovery plants.
   - (ii) Environmental objective:
     - (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.
   - (iii) Social objective: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.

(2) *Simulation optimisation methodology*: Mixed integer linear programming is the most commonly used modelling technique. For applying this method, some assumptions should be imposed, for example elimination of uncertainty in WEEE generation rate. Also the recovery rate of WEEE was assumed to be constant. Since RL has inherent uncertainty on quantity, quality, time and place of returns, therefore for the current work, a simulation-based optimisation technique will be applied for modelling all uncertain conditions.

(3) *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.

4. Designing sustainable recovery network

In order to design a sustainable RL network at national level, it was assumed that government and public sector investors are responsible for collection of all types of e-waste in each province. The proposed model considers all categories of WEEE as listed in Table 2. These categories are based on existing EOL treatment technologies in Iran and a report from a real case study by Huisman and Magalini (2007). However, due to lack of data in three categories (14, 15 and 16) in Iran, it was considered to be merged with other categories which had the similar recycling treatment, disassembly process or recycled materials. Authors also have assumed that all the generated WEEE that has not been collected prior to 2000 has ended up in landfills, so it was not considered as input data in the developed model.

In order to design the relevant RL network, there is a need to identify all sustainable development objectives for operations that take place in a WEEE recovery network for all the categories of the products listed in Table 2. Therefore, four groups of activities were identified which are influenced by WEEE recovery network (Fleischmann *et al.* 2003). They are as follows:

(1) *Collection*: To safely and completely collect WEEE from various provinces.
(2) *Transportation*: Transportation of WEEE products to collection centres and pre-treated products to recycling facilities
(3) *Pre-treatment and separation*: Only some WEEE groups are entirely free of hazardous substances. The others should be pre-treated in such ways that are suitable to be fed into recycling plants.
(4) *Recycling treatment plants*: They are the end node of a WEEE recovery network that comprises of different plants for recycling and treatment of various EOL products.

Table 2. WEEE categories (Huisman *et al.* 2007).

ID	WEEE category
1	Large household appliances
2	Cooling and freezing
3	Large household appliances (smaller items)
4	Small household appliances, lighting equipment, luminaries and 'domestic' medical devices
5	IT and telecom except CRT's
6	CRT monitors
7	LCD monitors
8	Consumer electronics except CRT's
9	CRT TV's
10	Flat panel TV's
11	Lighting equipment, lamps
12	Electrical and electronic tools
13	Toys, leisure and sports equipment
14	Medical devices (merged in category 4)
15	Monitoring and control instruments (merged in category 4)
16	Automatic dispensers (merged in category 1)

In the collection centres, WEEE should separately be collected and properly treated to segregate hazardous materials which cannot be treated using installed technologies in the plants. Then the generated materials are transported to the recovery plant.

According to 16 categories of WEEE, different recovery plants with different technologies can be selected. The type of recovery plant(s) used is affected by the government laws and the level of recovery required. Types of recovery plants are different in various countries. For example, under the Austrian 'Electro Ordinance' which transposes the WEEE directive into Austrian law, WEEE is categorised into and recovered through five different types of plants namely: large appliances, refrigeration equipment, Cathode ray tube (CRT), small electrical appliances, gas discharge lamps. In another example in the Netherlands, WEEE has been categorised into large white goods, small WEEE, CRTs and lamps. Types of WEEE recovery plants in other European countries can be found elsewhere (DTI 2006).

In this study, recovery plants were selected according to available technologies in Iran and categorised as follows:

- Fluorescent recycling plants.
- General plants for treatment of general equipment.
- Hi-tech plants for CRT and LCD.
- Coolant plants for treatment of coolants and freezers

However, other categorise as mentioned in the literature could easily be modelled without losing any generality and accuracy of the developed model.

Each plant can be established in the centre of each province with a pre-defined capacity for WEEE treatment. Iran has been divided into 30 provinces and the largest and most populated city in each province is considered as the centre of province. The EOL regions are assumed to be located in the cities that are the centre of each province as they are considered to be more suitable for installing the treatment plants and have better transportation infrastructure.

According to these activities, the conceptual model of the proposed WEEE RL network is presented in Figure 2.

By considering the assumptions made above, Figure 2 depicts the proposed conceptual model representing location and the type of recycling plants, the quantity of WEEE pre-treated products and the location of collection centres.

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

5. Methodology for modelling and optimisation of RL network

Computer simulation is a powerful tool in evaluating complex systems. These evaluations are usually in the form of responses to 'what if' questions (Azadivar 1999). A simulation experiment can be defined as a test or a series of tests in which meaningful changes are made to the input variables of a simulation model so that one may observe and identify the reasons for changes in the output variable(s). When the number of input variables is large and the simulation model is complex, the simulation experiment may become computationally prohibitive (Carson and Maria 1997).

For solving these issues, a simulation-based optimisation approach has emerged as a method which integrates optimisation techniques into simulation analysis in order to optimise the model under investigation. Simulation optimisation can be defined as the process of finding the best input variables among all the possibilities without explicitly evaluating each one (Carson and Maria 1997).

Hence, for solving the proposed problem, simulation-based optimisation method was applied. With this technique, a RL model is developed that also includes all the associated uncertainties within the proposed network. Figure 3 shows the main components of the developed model.

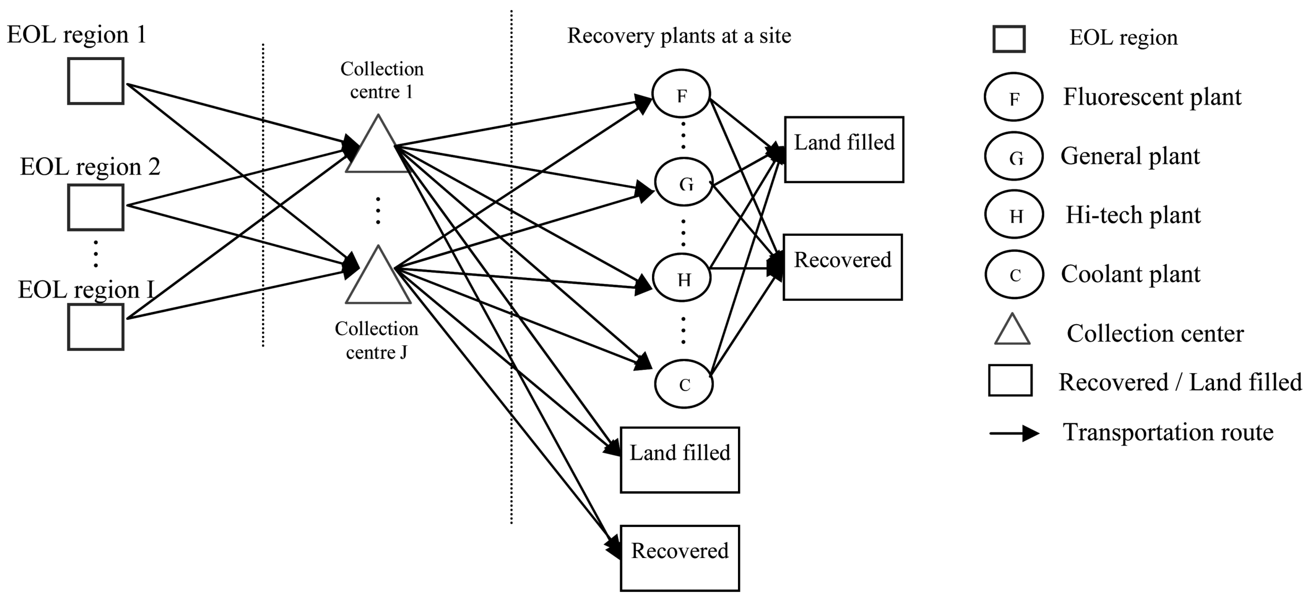

Figure 2. The proposed WEEE recovery network.

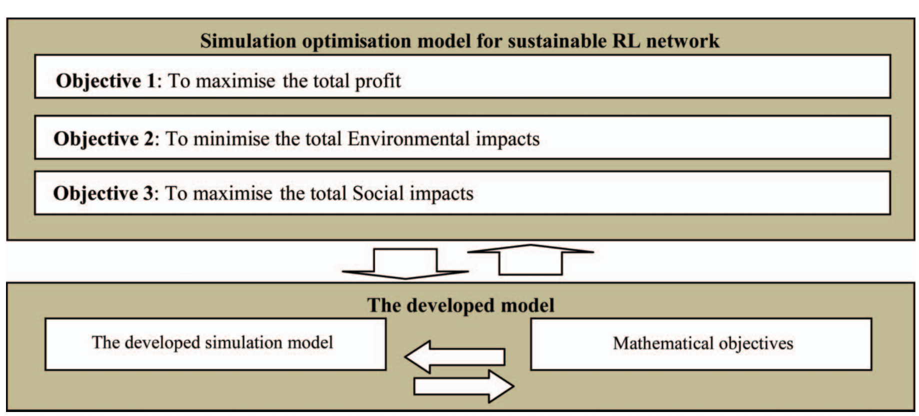

Figure 3. The main parts of the developed model.

As shown in Figure 3, the developed model has three main components:

(1) *Simulation part*: Simulation model is implemented in Arena simulation software (described in Section 5.1).
(2) *Optimisation part*: The objectives of the model are to optimise economical, environmental and social impacts of WEEE on the RL network. This part is implemented in Opt Quest software (described in Section 5.2).
(3) *Mathematical model*: The objective functions and constraints of the model are formulated as a mixed integer programming problem (described in Section 5.3).

5.1. Simulation model

In order to apply the Arena simulation software (Rockwell 2011), the model was broken down into three sub-models as shown in Figure 4.

The details of each sub-model in the Arena software are shown in Figures 5–7, respectively.

The starting point of the simulation model is the generation of WEEE in each province. As mentioned in Table 2, 13 waste categories are considered that are generated based on a probabilistic distribution functions (Figure 5).

Then these wastes are assigned to one of the collection centres. Then collection of the WEEE is assigned to one of the four types of recovery plants by using the probability distribution with respect to potential recovery of useful materials. Finally, recovered materials are sold in the market or disposed off (Figures 6 and 7).

5.2. Optimisation algorithm

As mentioned before, simulation-based optimisation method is applied to optimise the developed model. All objective functions and constraints are modelled in OptQuest software package (Kleijnen and Wan 2007) which is shown in Figure 8. The constraints of material flow between collection centres and recovery plants are also considered in the simulation model.

Opt Quest software is one of the most widely used tool for optimising simulation models (Kleijnen 2007). This software combines meta-heuristics method such as tabu search, neural networks and scatter search algorithm into simulation model and optimises the combination of simulation and mathematical model

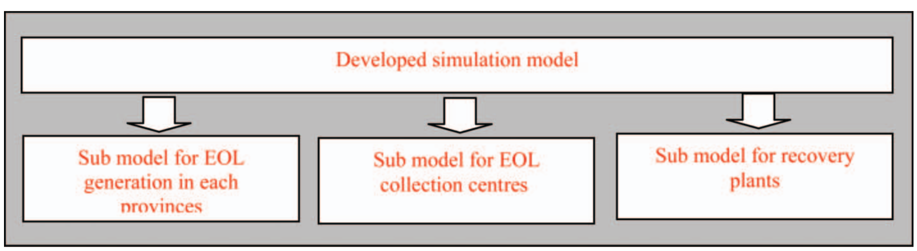

Figure 4. The hierarchy of the developed simulation sub-models.

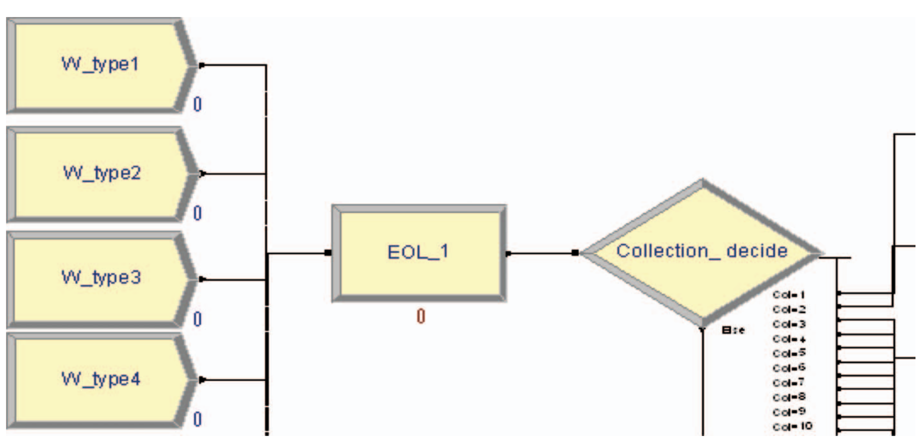

Figure 5. Sub-model for EOL generation in each provinces.

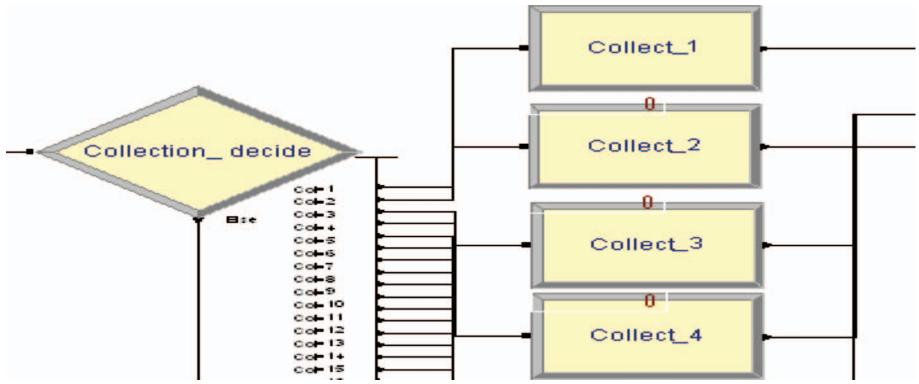

Figure 6. Sub-model for EOL collection centres.

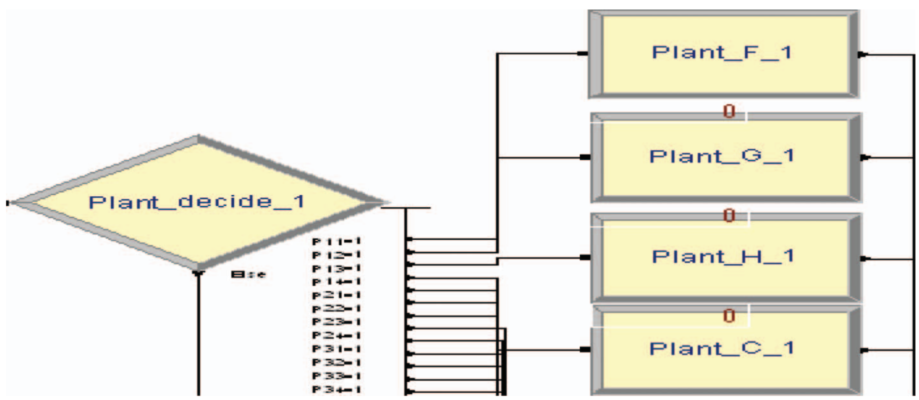

Figure 7. Sub-model for recovery plants.

(Rockwell 2011). The optimisation procedure in Opt Quest software is shown in Figure 9.

As shown in Figure 9, simulation optimisation is used to find the optimal settings of the input variables which optimise the objective function(s). After each run of the simulation model, the objective function(s) are calculated based on the simulation results and then new input parameters (based on above meta-heuristics methods) are set as input for the simulation model. This process continues until the pre-defined numbers of simulation runs are performed (Kleijnen 2007).

In the next section, the mathematical formulation of these objective functions is introduced.

5.3. *Mathematical objectives*

The objectives of the developed model are:

(1) *Economical objective function*: EOL of electrical and electronic equipments should no longer be considered as waste that should be sent to landfills or incineration facilities. Processing WEEE at least produces valuable second hand materials such as Cu, Pd, Au, etc that could be sold at local or international markets. Therefore, economical benefits of a RL network are one of the most important aspects of WEEE network. However, to achieve such benefits, one should first deal with the design and planning of a recovery network which requires expenditures that are: capital cost of installing and operating infrastructures, recycling facilities, collection centres and the cost of transportation between different nodes in the RL network.

(2) *Social objective function*: As mentioned in the literature review, most existing models have considered economic and environmental aspects of sustainable development and a very few researches have dealt with the social benefits of RL network (Morrissey and Browne 2004). In this work, the social issues and indicators in RL network (Carter and Jennings 2002, Vargas 2002, Dehghanian and Mansour 2009) were presented to a panel of experts consisting of the relevant governmental and organisational

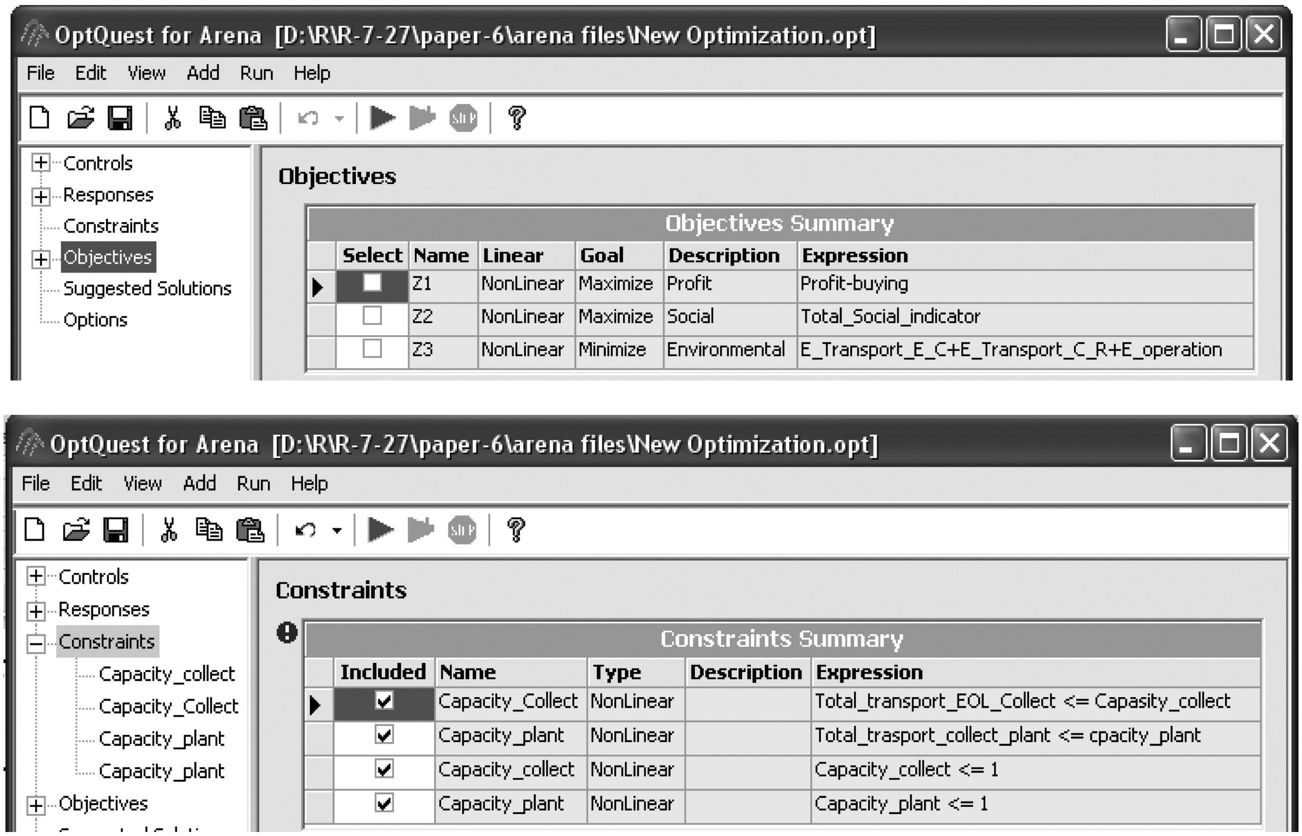

Figure 8. Objectives and constraints of the developed model.

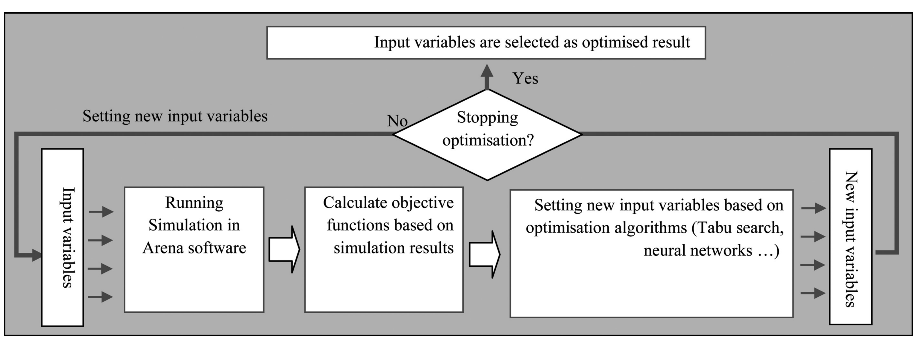

Figure 9. Opt Quest optimisation procedure (Rockwell 2011).

representatives and academic field. The framework of social sustainability indicators was identified and is introduced in Table 3.

Some social indicators in Table 3 are related to the geographical location of recovery plants, while some are related to recycling methods and possible product's health hazards while some are affected by both. These indicators are selected with respect to possibility of data gathering for each of them and could be changed without losing any generality of the developed model.

The Analytical Heretical Process (AHP) model (Saaty 1980) was applied in order to merge these indicators and create the total social indicator. By applying the AHP approach, the problem considered as a hierarchy, where the top-most node is the overall social indicator, while lower levels nodes consist of the criteria that are used for building the overall social indicator. Figure 10 shows The AHP hierarchy for the developed model.

(3) *Environmental objective function:* Waeger *et al.* (2011) presented the results of a combined

material flow analysis and life cycle assessment (LCA) study and calculated the overall environmental impacts of collection, dismantling and end-processing for the existing WEEE collection and recovery system as well as incineration and land fill scenarios. The Eco-indicator 99 methodology was used in different studies for calculating environmental impacts of WEEE (Consultants 2000, Frischknecht 2004). However, the calculation of exact environmental impacts for each type of WEEE is not the goal of this paper and these impacts are considered as input parameters for the developed model. Therefore, the environmental impacts for each type of WEEE are calculated based on the report by the ECE (2007).

Before introducing the mathematical modelling of the objective function, parameters and decision variables are introduced as follows:

Indices and parameters

- I Index set of provinces where $i = 1, \ldots, I$.
- J Index set of Collection centres where $j = 1, \ldots, J$.
- L Index set of potential treatment plants 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 percentage weight of WEEE type q in all type of WEEE
- C_S^H Fixed cost per unit time for opening and operating treatment plant type s with capacity h.
- C_J^H Fixed cost per unit time for opening and operating collection centres 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 province i to collection centre at site j.
- d_2JL Distance from collection centre j to potential treatment plant l.
- r Material type of WEEE
- B_{rq} fraction of WEEE type q with material type r
- C^T Cost of shipping 1 ton of WEEE per kilometre.
- O_r Selling price of material r
- EL_s Environmental impact of processing 1 tons of WEEE using plant s.
- P_q Selling and delivering price of WEEE type q
- EL^T Environmental impact of shipping 1 ton 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 in plant s, otherwise 0.
- V_{sl}^h 1 if plant s with capacity level h is located at site l, otherwise 0.
- V_j^h 1 if collection centre j with capacity level h is located at site j, otherwise 0.

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

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

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

$$Min\ Z_3 = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{q=1}^{Q} X_{ijq} d_{1ij} EL^T$$

$$+\sum_{j=1}^{J}\sum_{s=1}^{S}\sum_{l=1}^{L} Y_{jslq}(EL_s + d_{2jl} EL^T) \quad (3)$$

Constraints:

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

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

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

$$\sum_{h=1}^{H} V_j^h \le 1; \quad \forall j \quad (7)$$

Table 3. Social issues.

Indicators	Description
(1) Employment	Different EOL options may provide different number of employment opportunities.
(2) Damage to worker	Different EOL recyclers may be exposed to hazardous substances which are contained in WEEE products.
(3) Local development	Installing facilities in less developed areas results in community development which is an important issue in the government social responsibility.

$$\sum_{h=1}^{H} V_{sl}^h \le 1; \quad \forall s, l \quad (8)$$

$$V_{sl}^h \in (0, 1) \quad (9)$$

$$V_j^h \in (0, 1) \quad (10)$$

Equation (1) represents the economical impact of RL network. The first and second terms in Equation (1) correspond to the selling price of the recovered materials in collection centres or recovery plants. The third term deals with the purchasing price of WEEE. The fourth and fifth terms represent opening and operating costs for a collection centre and a recovery plant, respectively. The last two terms represent transportation cost from EOL region to collection centres and then to recovery plants. Equation (2) represents social impacts of the RL network. The first term in Equation (2) corresponds to social impacts of collection centres with respect to indicators shown in Table 3. Also the second term represents social impact of recovery plant with respect to the same indicators. Equation (3) minimises the total environmental impacts of the network. The first and second terms of Equation (3) represent the environmental impacts of WEEE transportation to collection centres and recovery plants, respectively.

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

6. The case study

The applicability of the developed model is illustrated by a case for the development of the RL network of WEEE in Iran.

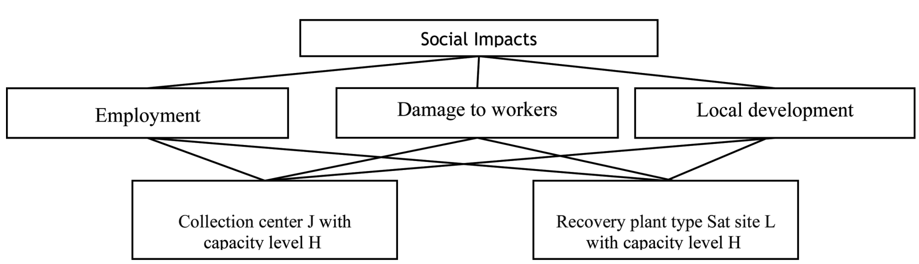

Figure 10. AHP model for social impact of each collection centres and recovery plants.

6.1. Assumptions and required data for implementing the model

Before implementing the model, some assumptions were made that are as follows:

- WEEE generated data: the data from 1995 through the end of 2010 was provided by Customs administration of Iran (IRICA 2011) and national statistics organisation (SCI 2011). Therefore, WEEE data for all types of WEEE were obtained from mentioned organisations. To obtain the collaboration and support of the IRICA and National Statistics Organisation, a formal letter was sent to each office and after interviewing with the relevant authority in the mentioned governmental organisations, the required data were gathered. The summarised collected data for 13 WEEE types (from 2000–2010) are presented in Figure 11.
  The collected data were partly validated by data presented by Taghipour *et al*. (2011) for eight categories of WEEE between 2005 and 2010. Then these data were 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*: As mentioned in Section 4, each province has the capability of having its own collection centre or shipping the waste to other provinces.
- *Collection centres*: the suggested capacities were assumed to be 10,000, 15,000, 20,000, 40,000 and 70,000 ton/year.

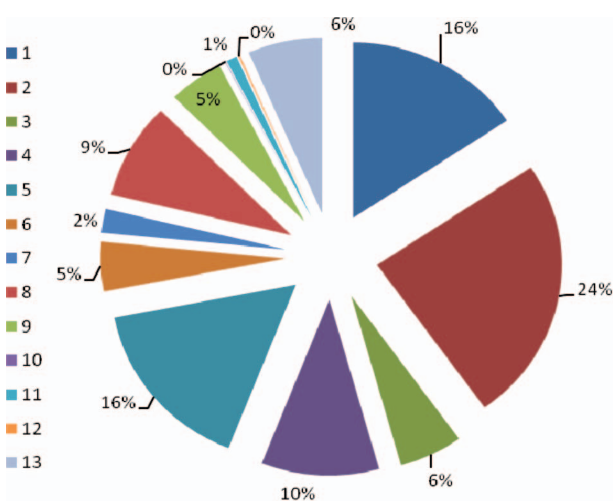

Figure 11. Summarised data for WEEE types in Iran during 2000–2011.

- *Recovery plants*: Collected WEEE in each collection centre is transported to provinces which are the potential sites for establishment of recovery plants with four different capacities (2000, 8000, 12,000 and 20,000). Each recovery plant is assumed to work 8 h 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.
- *Social objective*: To calculate social objective, the AHP method was used based on the indicators defined in Table 3 and Figure 4. Table 4 gives the relative weight of social indicators.
- *Transportation costs*: This is calculated based on shipping cost of 1 ton of scrap WEEE per kilometre. The type and capacity of vehicles

Table 4. Relative weight of social indicators.

Criteria	Relative weight (%)
Employment	58.4
Damage to workers.	28.2
National and local development	13.4

Table 5. Alternative capacity for each type of recovery plant.

Plant type	Opening and operating costs per year for minimum capacity (×10,000 Rials)	Profit of 1 ton of output (×10,000 Rials)	Environmental impact of 1 ton of WEEE (Pt)
Fluorescent plant	1,402,168	537	18.01
General plant	1,360,908	1169	23.73
Hi-tech plant	1,270,648	1060	25.12
Coolant plant	2,456,384	948	12.48

Table 6. Optimum solution regarding only one objective function (per year).

Selected objective function for optimisation	Optimised values with respect to selected objective function		
	Profit (×10,000Rials)	Environment (Pt)	Social (×1000)
Profit	131,259,143	7,701,750	351
Environment	96,100,803	4,862,784	332
Social	119,706,532	5,216,293	446

being used were not modelled in the proposed problem.

- The model was planned for 10 years.
- Other input parameters based on the panel of experts consisting of the relevant governmental and academic field are summarised in Table 5.

6.2. Results

As mentioned in Section 5.2 (Figure 6), the simulation optimisation procedure seeks an optimal solution with respect to specific objectives. This process continues until pre-defined numbers of simulation runs are performed. The results depend on the number of simulation runs. In the developed model, the algorithm was stopped after 700 runs and the best results between these runs considered as the optimal result. As already mentioned, the simultaneous minimisation of environmental impact and maximisation of profit and social objectives are the main objectives of the developed simulation model. However, at first, the model was optimised with respect to a single objective. The results regarding only one objective function is shown in Table 6.

Table 7. Optimal capacity (ton/year) for the recovery plant.

City	Plant type F	G	H	C
Tehran	2000	20,000	20,000	20,000
Esfahan	–	8000	8000	–
Shiraz	–	12,000	8000	8000
Mashhad	2000	20,000	–	8000
Tabriz	2000	18,000	12,000	8000
Hamadan	–	12,000	12,000	8000
Sari	–	8000	8000	–
Yazd	2000	20,000	12,000	–

Then according to the results of Table 7, the Weighted Percent of Deviation (WPD) of each result is calculated as total objective function (Dehghanian and Mansour 2009). Weighted Percent of Deviation is defined by Equation (10) where i is the number of replications.

$$WPD_i = \sum_{i=1}^{3} W_j * \frac{|f_j^i - f_j^*|}{f_j^*} \tag{10}$$

W_j indicates the weight of each objective function ($j = 1$ to 3), which is defined by decision makers and is related to the importance of the each objective function. The importance of each objective is considered equal (environmental=profit=social = 33.33%). f_j^i is the jth objective function value of solution i and f_j^* is the jth objective function value of optimal single objective problem. The model was run for 700 replications and the results are shown in Figure 12.

As shown in Figure 12, when number of replication increases, deviation of results is reduced. This reduction continues up to 600 replications. After this point, deviation increases. The reason is that the optimisation algorithm tries to get rid of the trap of local optimum point. Subsequently, if the results cannot be improved, starting point of generation is changed. The optimal profit, environmental and social objectives are 107,590,608 ($*10^4$) Rials, 5,512,056 Pt and 350 ($*10^3$) social impact, respectively. The detailed results of this optimal solution are shown in Tables 7 and 8.

Figure 13 represents the geographical locations of collection centres and recovery plants in Iran. According to Figure 13, Tables 8 and 9, government can determine the maximum capacity of each collection centre and type and capacity of a recovery plant in each city with respect to sustainable development

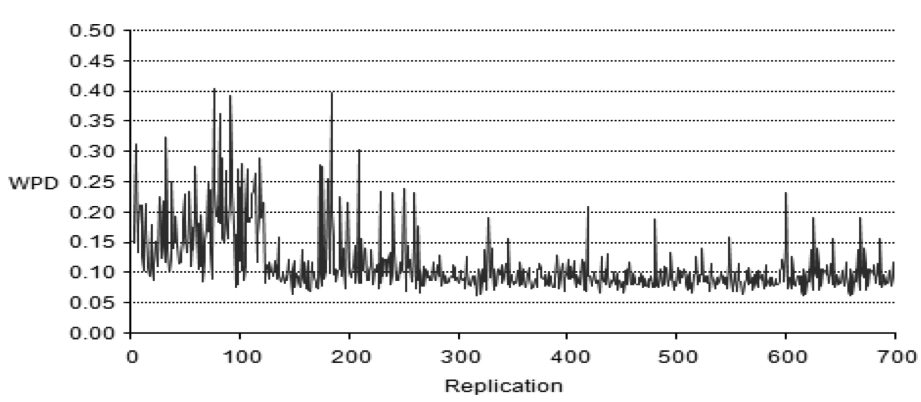

Figure 12. Optimal solution for the developed model.

Table 8. Optimal capacity (ton/year) for the collection centres

City	Collection centre capacity
Tehran	70,000
Esfahan	15,000
Shiraz	20,000
Mashhad	15,000
Tabriz	40,000
Hamedan	15,000
Sari	10,000
Yazd	20,000
Kerman	40,000
Shahrkord	40,000
Zanjan	20,000
Golestan	10,000

objectives for the next 10 years. Transportation cost accounts for 56% of total cost. Setting-up costs for collection centres and a recovery plant are 18% and 36% of the total cost, respectively.

The results shown in Tables 8 and 9 are obtained with the equal weight factor for each objective function. For comparing the optimal solutions with respect to weight of each objective, different sets of Wj were considered and respective WPD were calculated. The results are given in Table 9.

Figure 14 represents the normalised value of results for better understanding of the model.

According to Figure 14 and Table 9, decision makers can analyse the importance of each objective

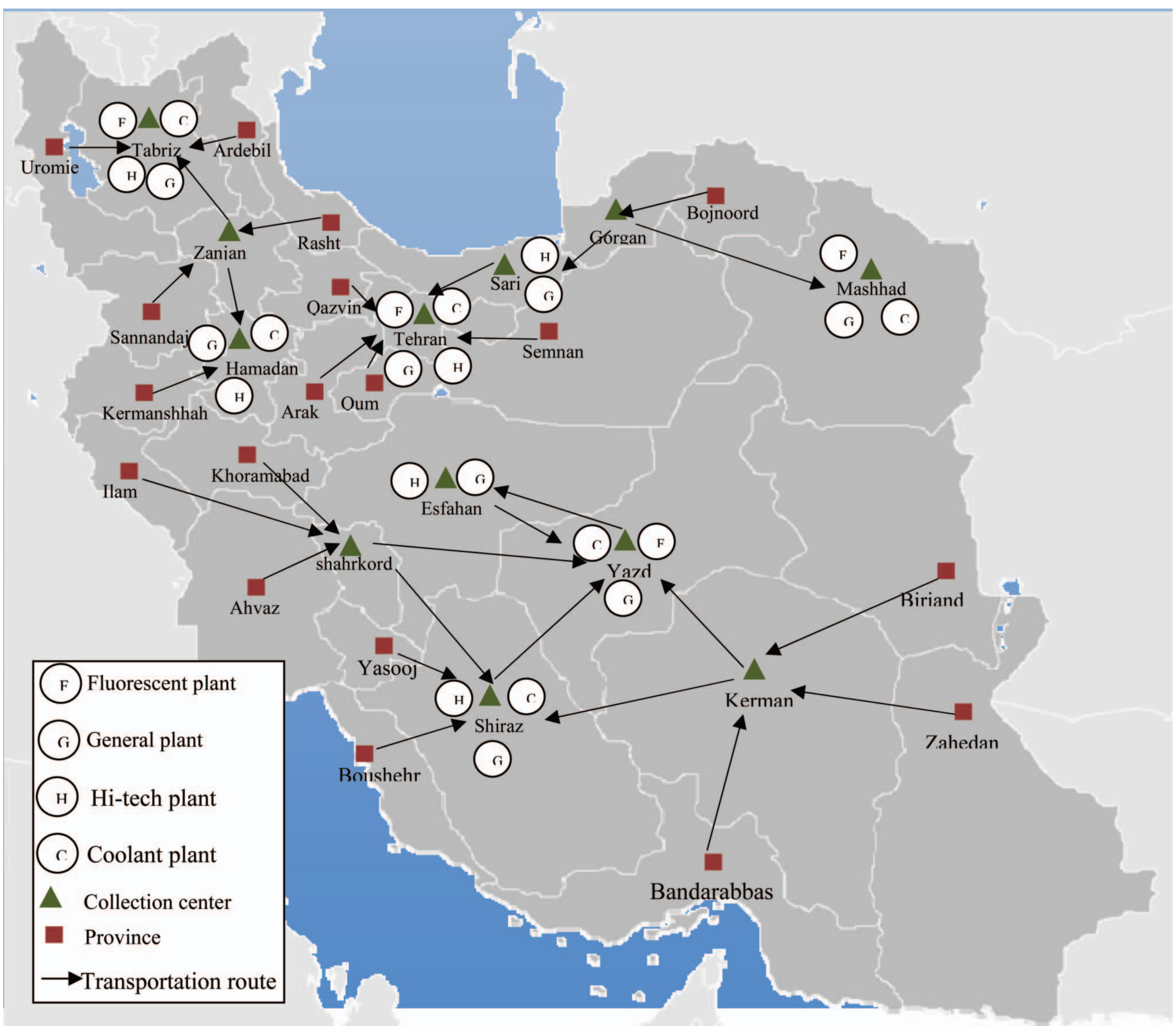

Figure 13. RL network layout for Iran.

Table 9. Optimal results for the proposed model.

Importance weight	Weight of each objective			Optimised objective		
	Environmental	Profit	Social	Profit ($\times 10^4$ Rials)	Environment (Pt)	Social ($\times$1000)
1	0.2	0.2	0.6	81,727,072	6,914,253	420
2	0.3	0.3	0.3	107,590,608	5,512,056	350
3	0.6	0.2	0.2	142,381,217	6,674,704	241
4	0.2	0.6	0.2	71,727,072	3,024,113	276

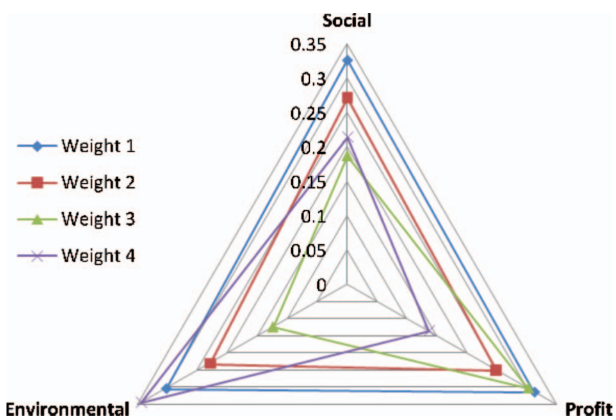

Figure 14. Comparison of optimised result with respect to weight of each objective.

on the optimal result. With respect to government preferences on importance of each objective, optimal solution can be selected. For example, by selecting importance weight number 3 from Table 10 (environmental = 0.6, profit = 0.2 and social = 0.2) the optimal environmental, economical and social impacts are 6,674,704 Pt, 142,381,217 (*10^3) Rials, 241 (*10^3) social impact, respectively

7. Conclusions and future research directions

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 the WEEE RL network. The environmental impacts of each network configuration were quantified by applying an Eco-indicator. Also social impacts of each decision were quantified by AHP methodology. Simulation optimisation method was applied for optimising the developed model and results were analysed. The proposed model was examined through an example by using the WEEE data in Iran.

Some of the future research directions that can be derived from the work are presented here:

(1) In this paper, social impacts are modelled with three indicators namely: employment, damage to worker, local development. The future research may include other social issues such as public health and safety in to the model.
(2) In the presented work, a simulation 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.
(3) Uncertainties related to the WEEE generations rate were modelled by simulation optimisation method. Incorporating the uncertainties associated with the costs and revenues of the RL network is recommended for future research.

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