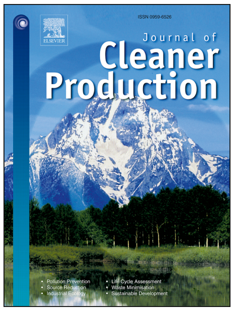

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A multi-objective robust optimization model for site-selection and capacity allocation of municipal solid waste facilities: A case study in Tehran

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Abstract: This paper introduces a multi-objective robust optimization model for a municipal solid waste (MSW) management system consisting of customers, transfer stations, landfills, recycle plants, and waste transport vehicles. The proposed model addresses the economic, environmental, and social perspectives of this system simultaneously by minimizing the total cost, the greenhouse gas emission, and the resulting visual pollution, respectively. This model can aid decision makers to locate the optimal sites of MSW recycling and disposal facilities, optimize the capacity allocation of landfills to transfer stations and population centers, optimize the capacity allocation of transfers stations and recycle plants to population centers, determine the most suitable technology for each operation, and find the right number and type of transport vehicles based on aforementioned objectives. Comparing to prior studies, considering all three dimensions of sustainability (i.e. economic, environmental and social) simultaneously, attempting to locate all three major MSW processing and disposal facilities (namely, transfer stations, recycling plants, and landfills) at the same time, and Considering uncertainties involved in this group of facility location problems are the innovations of this study. The proposed model, which is also fully compatible with the waste segregation at source approach, was validated by the use of real data for long-term planning of Tehran's MSW management system by examining five candidate sites for the construction of new facilities. The results show the efficiency of proposed model.

Keywords: Facility location, Capacity allocation, Municipal Solid Waste management, Recycle factories, Sustainable optimization, Multi-objective optimization.

Nomenclature

Sets

g	Set of possible sites for facilities
i	Set of population centers $i = 1,...,m$
j	Set of candidate sites for landfills $j = 1,...,n$
ℓ	Set of candidate sites for transfer stations $\ell = 1,...,s$
r	Set of candidate sites for recycle plants $r = 1,..., f$
k	Set of technologies for landfills $k = 1,...,a$
p	Set of technologies for transfer stations $p = 1,...,b$
o	Set of technologies for recycle plants $o = 1,...,d$
q	Set of technologies for semi-trailer trucks $q = 1,...,\mathrm{e}$
s	Set of scenarios related to population centers demand $s = 1,...,S$

Parameters

w_i	Number of customers in population center i
γ	Amount of non-recyclable waste generated by each customer $\left({}^{ton}/_{year}\right)$
λ	Amount of recyclable waste generated by each customer $\left({}^{ton}/_{year}\right)$
Cap_{jk}^{L}	Capacity of landfill j with technology k $\left({}^{ton}/_{year}\right)$
$Cap_{\ell p}^{T}$	Capacity of transfer station ℓ with technology p $\left({}^{ton}/_{year}\right)$
Cap_{ro}^{R}	Capacity of recycle plant r with technology o $\left({}^{ton}/_{year}\right)$
Cap^{CT}	Load-carrying capacity of collection trucks (ton)
Cap^{TR}	Load-carrying capacity of transport trucks (ton)
Cap_{q}^{ST}	Load-carrying capacity of a semi-trailer truck with technology q (ton)
$VCap_{q}^{ST}$	Volume-carrying capacity of a semi-trailer truck with technology q (m^3)
FC_{jk}^{L}	Fixed cost of opening a landfill with technology k at node j $(\$)$
OC_{k}^{L}	Annual operational cost of landfills with technology k $\left({}^{\$}/_{ton}\right)$
$FC_{\ell p}^{T}$	Fixed cost of opening a transfer station with technology p at node ℓ $(\$)$

OC_p^T	Annual operational cost of transfer stations with technology p $\left({}^{\$}/_{ton}\right)$
FC_{ro}^R	Fixed cost of opening a recycle plant with technology o at node r $(\$)$
OC_o^R	Annual operational cost of recycle plants with technology o $\left({}^{\$}/_{ton}\right)$
PRM_o	Selling price of recycled materials produced by a recycle plant with technology$o$ $\left({}^{\$}/_{ton}\right)$
$\ddddot{TRP}$	Amount of greenhouse gas emission from each collection truck $\left({}^{gr}/_{km}\right)$
$\hat{TRP}_q$	Amount of greenhouse gas emission from a semi-trailer truck with technology q $\left({}^{gr}/_{km}\right)$
$\overline{TRP}$	Amount of greenhouse gas emission from each transport truck $\left({}^{gr}/_{km}\right)$
LP_k	Amount of greenhouse gas emission from process of each ton of non-recyclable waste in a landfill with technology k
TP_p	Amount of greenhouse gas emission from process of each ton of non-recyclable waste in a transfer station with technology p
RP_o	Amount of greenhouse gas emission from process of each ton of recyclable waste in a recycle plant with technology o
ϕ^L	Visual pollution factor for each landfill $\left({}^{km^2}/_{person}\right)$
ϕ^T	Visual pollution factor for each transfer station $\left({}^{km^2}/_{person}\right)$
ϕ^R	Visual pollution factor for each recycle plant $\left({}^{km^2}/_{person}\right)$
MP^C	Maximum GHG emission capacity imposed on each population center
MP^L	Maximum GHG emission capacity imposed on each landfill
MP^T	Maximum GHG emission capacity imposed on each transfer station
MP^R	Maximum GHG emission capacity imposed on each recycle plant
$\ddddot{TC}$	Unit transportation cost of each collection truck $\left({}^{\$}/_{km}\right)$
$\hat{TC}_q$	Unit transportation cost of each semi-trailer truck $\left({}^{\$}/_{km}\right)$
$\overline{TC}$	Unit transportation cost of each transport truck $\left({}^{\$}/_{km}\right)$
$d_{ij}, d_{i\ell}, d_{ir}, d_{\ell j}$	Distances between customer i , transfer station ℓ, landfill j , and recycle plant r (km)
α	Compaction factor related to reducing volume of the waste in transfer stations (this parameter shows how much the volume of waste after the compaction will be reduced.) $\left({}^{m^3}/_{ton}\right)$

β	The percentage of recycled materials which are sold to customers (the rest part is promotionally given to customers)
ψ	A large positive number
γ^s	Amount of non-recyclable waste generated by each customer under scenario s $\left({}^{ton}\!/_{year}\right)$
λ^s	Amount of recyclable waste generated by each customer under scenario s $\left({}^{ton}\!/_{year}\right)$
η	Weight of variability
$\bar{\lambda}$	Weight of expected value
pr_s	Probability of occurrence of scenario s
κ	Penalty cost for each ton of non-recyclable waste which is not collected
ζ	Penalty cost for each ton of recyclable waste which is not collected
χ_1	Weight of first objective function
χ_2	Weight of second objective function
χ_3	Weight of third objective function
Z_C^S	First dimensionless objective function under scenario s
Z_P^S	Second dimensionless objective function under scenario s
Z_V^S	Third dimensionless objective function under scenario s

Decision variables

Location variables

y_{jk}	A zero-one variable that equals 1 if a landfill with technology k is established at location j, 0 otherwise
$\nu_{\ell p}$	A zero-one variable that equals 1 if a transfer station with technology p is established at location ℓ, 0 otherwise
ω_{ro}	A zero-one variable that equals 1 if a recycle plant with technology o is established at location r, 0 otherwise

Allocation variables

z_{ij}	A zero-one variable that equals 1, if all non-recyclable waste from population center i is shipped directly to landfill j, 0 otherwise
$x_{i\ell}$	A zero-one variable that equals 1, if all non-recyclable waste from population center i is shipped to transfer station ℓ, 0 otherwise
h_{ir}	A zero-one variable that equals 1, if population center i and recycle plant r are related, 0 otherwise

$u_{\ell jq}$	A continuous variable that measures the non-recyclable waste quantity that is shipped from transfer station ℓ to landfill j by a semi-trailer truck with technology q $\left({ton}/{year}\right)$
z_{ij}^{s}	A zero-one variable that equals 1, if all non-recyclable waste from population center i is shipped directly to landfill j under scenario s, 0 otherwise
$x_{i\ell}^{s}$	A zero-one variable that equals 1, if all non-recyclable waste from population center i is shipped to transfer station ℓ under scenario s, 0 otherwise
h_{ir}^{s}	A zero-one variable that equals 1, if population center i and recycle plant r are related under scenario s, 0 otherwise
$u_{\ell jq}^{s}$	A continuous variable that measures the non-recyclable waste quantity that is shipped from transfer station ℓ to landfill j by a semi-trailer truck with technology q under scenario s $\left({ton}/{year}\right)$

Transport variables

NCL_{ij}	Number of collection trucks for shipping non-recyclable waste from population center i to landfill j
$NCT_{i\ell}$	Number of collection trucks for shipping non-recyclable waste from population center i to transfer station ℓ
NCR_{ir}	Number of collection trucks for shipping recyclable waste from population center i to recycle plant r
$NTL_{\ell jq}$	Number of semi-trailer trucks with technology q for shipping non-recyclable waste from transfer station ℓ to landfill j
NRC_{ri}	Number of transport trucks for shipping recyclable waste from recycle plant r to population center i
NCL_{ij}^{s}	Number of collection trucks for shipping non-recyclable waste from population center i to landfill j under scenario s
$NCT_{i\ell}^{s}$	Number of collection trucks for shipping non-recyclable waste from population center i to transfer station ℓ under scenario s
NCR_{ir}^{s}	Number of collection trucks for shipping recyclable waste from population center i to recycle plant r under scenario s
$NTL_{\ell jq}^{s}$	Number of semi-trailer trucks with technology q for shipping non-recyclable waste from transfer station ℓ to landfill j under scenario s
NRC_{ri}^{s}	Number of transport trucks for shipping recyclable waste from recycle plant r to population center i under scenario s

Other variables

δ_i^s	Amount of unmet demand related to non-recyclable waste in population center i under scenario s
τ_i^s	Amount of unmet demand related to recyclable waste in population center i under scenario s

1. Introduction

Waste management is one of the major health and environmental concerns of every large human community, because if not managed properly, the produced wastes can contaminate surface and ground water, soil and air on a grand scale and very rapidly. Municipal waste consists primarily of everyday garbage, but management of this garbage has become a persistent challenge for many developing countries because of their fast population growth, poverty and lack of proper investment by governments or responsible authorities (Jara-Samaniego et al., 2017). The steady increase of global waste generation rate due to ongoing population growth and economic development highlights the importance and necessity of an effective approach to design and planning of MSW management systems (Xi et al., 2010).

Mathematical programming models capable of improving the performance of MSW systems by optimizing the location of their facilities and allocation of facilities to each other are of significant utility in this respect (see, e.g., Habibi et al., 2017). The literature of this field contains a variety of models that differ based on the assumptions considered by their developers. In a basic household waste collection process, the garbage gathered from population centers is first sent to transfer facilities, where it is unloaded from municipal collection trucks and loaded into larger trucks in order to be transported in mass to landfills (Guneri et al., 2009; Takano & Arai, 2009). Dispatching the MSW through transfer stations increases the efficiency of collection process and reduces the overall transport cost, energy consumption, truck traffic, and air pollution. Given the effect of waste collection and disposal process on nature and human life, locating landfills and transfer facilities in accordance with required standards is one of the essential objectives of urban development plans (Aversa et al., 2005).

Recycling is the process of collecting, reprocessing, and recovery of certain materials in order to produce new materials and products with a significant contribution to economy as well as environmental health (Jahre, 1995; Xie & Ma, 2016). Zaman (2016) has shown that there is a direct positive relationship between the waste generation and income, which means the more waste is, the more income is, which points to the presence of a potential for economic use of waste through methods such as recycling. Thus, waste management is not only a great challenge but also a great opportunity to convert waste into valuable materials or energy (Peltola et al., 2016). Hence, when investigating the MSW management systems, it is essential to pay due attention to not only landfills and transfer stations but also recycling facilities so as to reap the possible economic and environmental advantages of this operation.

The presence of recycling facilities alongside other facilities of the MSW system necessitates adopting a reverse logistic approach, which is a process of moving waste from their typical final destination for the purpose of capturing value and in waste management, recycling waste to reuse is a reverse logistic, rather than the forward approach followed in traditional logistics, and leads to formation of a closed-loop supply chain from logistics perspective (Jahre, 1995; Alumur & Kara, 2007; Cappanera et al., 2003; Samanlioglu, 2013; Zhao & Verter, 2015; Amalnick & Saffar, 2017).

One of the popular approaches in evaluation of reverse and closed-loop logistics systems is the incorporation of sustainability concepts into optimization process. In recent decades, organizations seeking to globalize their operations have had to improve not only their economic, but also their social and environmental performance (Tajbakhsh & Hassini, 2015; Gold et al., 2010; Luken & Van Rompaey, 2008). Carter & Rogers (2008) define the concept of sustainability in supply chain as integration of environmental, social and economic measures allowing an organization to achieve long-term sustainable economic performance. Although it is essential to understand the nature and mutual relationships of economic, social and environmental criteria alongside each other, the complexity of quantification of social impacts have led to rather little attention of research to social criteria. In particular, studies on social sustainability of supply chain in developing countries are very rare (Mani et al., 2016). Scholars (Lafferty & Langhelle, 1999; Sharma & Ruud, 2003) define social sustainability as an “ethical code of conduct for human survival and outgrowth that needs to be accomplished in a mutually inclusive and prudent way”.

1.1. Uncertainty in MSW models

Like other real-world optimization problems where uncertainty plays a major role and should be considered accordingly to achieve accurate results, MSW handling problem is also involved with some uncertainties that need to be addressed properly. In MSW management system, uncertainties in the costs (relating to location and transportation, treatment and disposal) may affect the factors and objectives and consequently the decision-making processes (Huang et al., 1993). As a result, various methods such as fuzzy, stochastic, and interval mathematical programming approaches have been proposed to deal with MSW management system planning (Kirca & Erkip, 1988; Zhu & ReVelle, 1990; Huang et al., 1993, 1995, 2001; Leimbach, 1996; Chang & Wang, 1995, 1996, 1997; Chang et al., 1997; Maqsood & Huang, 2003).

In the following, we review a number of notable works that have been considered uncertainties in the field of MSW management system. Lahdelma et al. (2002) proposed Stochastic Multi-criteria

Acceptability Analysis with Ordinal criteria (SMAA-O) method for discrete multi-attribute problems where data is uncertain or inaccurate. Biswas & De (2016) developed a Fuzzy chance constrained programming approach to minimize the net system costs and maximize the revenue of several treatment facilities, and used the fuzzy goal programming to address the uncertainty in model parameters. Koo et al. (1991) proposed a framework based on Waste Resources Allocation Program (WRAP) and fuzzy set theory with the aim of establishing a tradeoff between the objectives, costs, environmental quality and managerial efficiency, and demonstrated its performance with a case study to determine the optimal location of a waste treatment hazardous facility in southwestern Korea. Davila et al. (2005) introduced a game theory based gray integer programming to optimize system performance and used it to perform a cost analysis on two landfills in Texas, US. Li et al. (2008) developed a two-stage stochastic optimization model for MSW planning in Canada. Their model facilitates the scenario analysis of different policies involved with different economic penalty levels. Li et al. (2012) developed a Scenario based Fuzzy-stochastic Quadratic Programming (SFQP) for dealing with uncertainties when determining the optimal MSW management policy by utilizing fuzzy functions and sets in the course of optimization process. Berglund & Kwon (2014) studied robust facility location problem for the transport of hazardous substances with HAZMAT routing. They also used numerical data to demonstrate the impact of uncertainty and robust optimization on the Hazmat location-routing problem.

1.2. Related studies

There have been quite many studies on location of MSW management and disposal facilities based on different considerations and assumptions. In the following, we review a number of notable works in this field. Alumur & Kara (2007) developed a multi-objective location-routing model to minimize the total costs and risk of transportation to determine location of waste treatment sites, the appropriate technologies for this operation, location of landfill sites, and the routes to these sites. Erkut et al. (2008) developed a multi-objective mixed integer linear programming model to solve the site-selection and capacity allocation problem for MSW facilities in regional and provincial scales according to economic and environmental criteria. Xi et al. (2010) developed a Mixed Integer Linear Programming (MILP) model for planning long-term MSW management decisions. Minimizing the system cost was the main objective of their model and the decision variables of their model were the continuous variables of waste flows. Coutinho-Rodrigues et al. (2012) developed a bi-objective mixed integer programming model that minimizes the investment costs and resulting discontent among local residents simultaneously to determine the number of facilities that should be established, their capacity and location, and the contribution of each facility to meet the demand. Chatzouridis & Komilis (2012) developed an applied nonlinear mathematical model aimed at optimizing the design of

MSW collection network. Assuming that waste generation rates and locations are known, the first objective function of their model decides whether transfer stations should be built, determines the relationship between network nodes, and then minimizes the cost accordingly. They also used a Geographical Information System (GIS) location methodology to determine the exact location of landfills. Berglund, P. G., & Kwon (2014) studied the sustainable facility location for the transport of hazardous materials (HAZMAT). In their model, location of processing facilities is determined by considering a network of nodes and arcs, where the total cost, including the fixed cost of establishing facilities, transport costs and the potential risk, is minimized. Ardjmand et al. (2015) developed a mathematical model for location-routing of MSW processing and disposal facilities. Their model also considers the risks and costs of transportation of recycled materials from facilities to customers. Ghiani et al. (2014) studied two decision problems concerning the MSW collection plan, collection sites, and the area of collection service. They developed an exact method and a heuristic to determine the location, capacity, and features of desegregated waste bins in urban areas. Eiselt & Marianov (2014) introduced a model for determining the location and capacity of landfills and transfer stations. In their bi-objective model, common costs and pollution are minimized in two separate objective functions. Eiselt & Marianov (2015) studied the landfill location problem and used the decision models to introduce a general model for cost minimization. In this article, a number of multi-criteria decision models commonly used for landfill location were also explained. Asefi et al. (2015) introduced a mathematical formulation for location and routing problems concerning MSW disposal facilities. Jabbarzadeh et al. (2016) developed a multi-objective optimization model for a MSW network consisting of population centers, transfer stations, landfills and collection vehicles. They solved the model with a solution method based on interactive fuzzy programming logic. The advantages and disadvantages of these studies have been summarized in Table 1.

****Table 1****

The steady growth in world’s MSW generation rate and the importance of location and allocation of MSW processing and disposal facilities highlights the need for a comprehensive model capable of accounting for all facilities of MSW disposal systems including transfer stations, recycling plants, and landfills.

- As the summary of literature in Table 1 demonstrates, none of the mathematical models provided for facility location in MSW management context has considered all three dimensions of sustainability (i.e. economic, environmental and social) simultaneously.

- As can be seen, all models have defined the objectives as minimization of a summation regardless of social justice.
- Also, only a few studies have attempted to locate all three major MSW processing and disposal facilities (namely, transfer stations, recycling plants, and landfills) at the same time.
- It can also be seen that despite the potentially profound effect of uncertainties involved in this group of facility location problems, models that have considered this issue are quite rare.

In this article, we attempt to contribute to the literature of MSW management facility location by addressing the above mentioned gaps in this literature. To do so, we propose a multi-objective robust optimization model for site-selection and capacity allocation of all MSW recycling and disposal facilities in an MSW management system. The model to be described is formulated as a tri-objective mathematical optimization model that minimizes, simultaneously, the cost of required facilities and vehicles, greenhouse gas emissions caused by these facilities and vehicles, and social impacts due to visual pollution caused by establishment of facilities near population centers. This model allows decision makers to optimize the location of MSW recycling and disposal facilities, the allocation scheme, the type of MSW processing and handling technology, the capacity of each facility, and the number of vehicles required to transport processed and unprocessed materials between facilities.

The rest of this paper is organized as follows: In Section 2, framework and overall structure of MSW disposal and recycling system and the optimization model in both deterministic and robust expressions are described. Section 3 explains how the proposed model is used to study the Tehran's long-term MSW management plan, and Section 4 presents the results of this case study and the effects of the proposed model on them. The last section concludes the paper and suggests some directions for future research.

2. Methodology

In this paper, we formulate an optimization model for a MSW system consisting of population centers (MSW generation points), transfer stations, recycling plants and landfills. In this system, population centers generate two types of MSW: recyclable and non-recyclable. We assume that non-recyclable MSW is transported to landfills in two ways: 1) direct transport: using collection trucks to transport MSW directly from population centers to landfills 2) indirect transport: using collection trucks to accumulate the collected MSW at transfer stations, compacting them into modular cubes, and then using semi-trailer trucks to transport the compacted cubes to landfills. Compaction of non-recyclable MSW at transfer stations reduces the cost of transport, especially over long-distances. It is assumed that recyclable MSWs generated in population centers will be transported by collection trucks to recycling plants, where they will be recycled; then a part of resulting material will be used to produce a number of products, which will be rewarded to participating population to promote the operation. The remaining part of material will be sold back to population centers. Transfer stations, landfills, recycling plants, and semi-trailer trucks (transporting non-recyclable MSW from transfer stations to landfills) may have different technologies, capacities and produce different amounts of greenhouse gases. Figure 1 illustrates overall structure of this MSW system.

****Figure 1****

The objective is to determine the following decisions simultaneously:

1. The number of transfer stations to be established.
2. The location of each transfer station.
3. The type of technology to be used in each transfer station.
4. The number of landfills to be established.
5. The location of each landfill.
6. The type of technology to be used in each landfill.
7. The number of recycling plants to be established.
8. The location of each recycling plant.
9. The type of technology to be used in each recycling plant.
10. The number and type of semi-trailer trucks to be used at each transfer station.
11. The number of collection trucks to be used at each population center.
12. The number of transport trucks to be used at each recycling plant.
13. The amount of MSW to be transported from each transfer station to landfills.
14. How to allocate landfill capacity to transfer stations.
15. How to allocate landfill capacity to population centers.
16. How to allocate transfer station capacity to population centers.
17. How to allocate recycling plant capacity to population centers.

The above decisions will be determined by using a multi-objective optimization model that minimizes the total cost of operation, the amount of greenhouse gas emission, and adverse effects of construction and presence of MSW disposal facilities on local residents (visual pollution). Visual pollution refers to the impacts of pollution that damage the people ability to enjoy seeing a view. It also creates negative changes in the natural environment and disturbs the visual areas (Yilmaz & Sagsoz, 2011; Nagle, 2009).

2.1. Deterministic model

In this section the main model is being described. The mathematical formulation proposed for this problem consists of three objective functions. The first objective function minimizes the cost of establishing and operating MSW management facilities and the cost of transportation between them. The second objective function minimizes the emissions to be produced by facilities and different transport vehicles. The third objective function minimizes the maximum of visual pollution for each population center.

$$\begin{aligned}
&\text{Minimize } z_c = \sum_{\ell}\sum_{p} FC^{T}_{\ell p}\, v_{\ell p} + \sum_{i}\sum_{\ell}\sum_{p} OC^{T}_{p}\gamma w_i\, x_{i\ell} + \sum_{j}\sum_{k} FC^{L}_{jk}\, y_{jk} + \sum_{j}\sum_{k} OC^{L}_{k}\Big(\sum_{i}\gamma w_i\, z_{ij} + \sum_{\ell}\sum_{q} u_{\ell jq}\Big)\\
&+\sum_{r}\sum_{o} FC^{R}_{ro}\,\omega_{ro} + \sum_{i}\sum_{r}\sum_{o} OC^{R}_{o}\,\lambda\, w_i\, h_{ir} - \sum_{i}\sum_{r}\sum_{o} PRM_o\,\beta\,\lambda\, w_i\, h_{ir}\\
&+\sum_{i}\sum_{\ell}\ddddot{TC}\, NCT_{i\ell}\, d_{i\ell} + \sum_{i}\sum_{j}\ddddot{TC}\, NCL_{ij}\, d_{ij} + \sum_{\ell}\sum_{j}\sum_{q}\hat{TC}_q\, NTL_{\ell jq}\, d_{\ell j} + \sum_{i}\sum_{r}\ddddot{TC}\, NCR_{ir}\, 2d_{ir} + \sum_{r}\sum_{i}\overline{TC}\, NRC_{ri}\, d_{ir} \qquad (1)
\end{aligned}$$

$$\begin{aligned}
&\text{Minimize } z_p = \sum_{\ell}\sum_{p} TP_p\, v_{\ell p} + \sum_{j}\sum_{k} LP_k\, y_{jk} + \sum_{r}\sum_{o} RP_o\,\omega_{ro}\\
&+\sum_{i}\sum_{\ell}\ddddot{TRP}\, NCT_{i\ell} d_{i\ell} + \sum_{i}\sum_{j}\ddddot{TRP}\, NCL_{ij}\, d_{ij} + \sum_{\ell}\sum_{j}\sum_{q}\hat{TRP}_q\, NTL_{\ell jq}\, d_{\ell j} \qquad (2)\\
&+\sum_{i}\sum_{r}\ddddot{TRP}\, NCR_{ir}\, 2d_{ir} + \sum_{r}\sum_{i}\overline{TRP}\, NRC_{ri}\, d_{ir}
\end{aligned}$$

$$\text{Minimize } Z_v = \max_{i}\left\{ w_i \left[\sum_{j}\frac{\phi^{L}\left(\sum_{i'}\gamma w_{i'}\, z_{i'j} + \sum_{\ell}\sum_{q} u_{\ell jq}\right)}{\left(d_{ij}+\varepsilon\right)^2} + \sum_{\ell}\frac{\phi^{T}\left(\sum_{i'}\gamma w_{i'}\, x_{i'\ell}\right)}{\left(d_{i\ell}+\varepsilon\right)^2} + \sum_{r}\frac{\phi^{R}\left(\sum_{i'}\lambda\, w_{i'}\, h_{i'r}\right)}{\left(d_{ir}+\varepsilon\right)^2} \right]\right\} \qquad (3)$$

Subject to:

$$\sum_{i}\sum_{\ell}\ddddot{TRP}\, NCT_{i\ell} d_{i\ell} + \sum_{i}\sum_{j}\ddddot{TRP}\, NCL_{ij} d_{ij} + \sum_{i}\sum_{r}\ddddot{TRP}\, NCR_{ir} d_{ir} \le MP^{C} \qquad (4)$$

$$\sum_{\ell}\sum_{p} TP_p v_{\ell p} + \sum_{\ell}\sum_{j}\sum_{q}\hat{TRP}_q\, NTL_{\ell jq} d_{\ell j} \le MP^{T} \qquad (5)$$

$$\sum_{j}\sum_{k} LP_k y_{jk} \le MP^{L} \qquad (6)$$

$$\sum_{r}\sum_{o} RP_o \omega_{ro} + \sum_{r}\sum_{i}\overline{TRP}\, NRC_{ri} d_{ir} + \sum_{i}\sum_{r}\ddddot{TRP}\, NCR_{ir} d_{ir} \le MP^{R} \qquad (7)$$

$$z_{ij} \le \sum_{k} y_{jk} \qquad \forall i, j \qquad (8)$$

$$x_{i\ell} \le \sum_{p} v_{\ell p} \qquad \forall i,\ell \tag{9}$$

$$h_{ir} \le \sum_{o} \omega_{ro} \qquad \forall i,\mathrm{r} \tag{10}$$

$$\sum_{\ell}\sum_{q} u_{\ell jq} \le \psi \sum_{k} y_{jk} \tag{11}$$

$$\sum_{j} z_{ij} + \sum_{\ell} x_{i\ell} = 1 \qquad \forall i \tag{12}$$

$$\sum_{r} h_{ir} = 1 \qquad \forall i \tag{13}$$

$$\sum_{q}\sum_{j} u_{\ell jq} = \sum_{i} \gamma w_i x_{i\ell} \qquad \forall \ell \tag{14}$$

$$\sum_{i} \gamma w_i x_{i\ell} \le \sum_{p} Cap^{T}_{\ell p} v_{\ell p} \qquad \forall \ell \tag{15}$$

$$\sum_{i} \gamma w_i z_{ij} + \sum_{\ell}\sum_{q} u_{\ell jq} \le \sum_{k} Cap^{L}_{jk} y_{jk} \qquad \forall j \tag{16}$$

$$\sum_{i} \lambda w_i h_{ir} \le \sum_{o} Cap^{R}_{ro} \omega_{ro} \qquad \forall r \tag{17}$$

$$\sum_{p} \mathrm{v}_{gp} + \sum_{k} y_{gk} + \sum_{o} \omega_{go} \le 1 \qquad \forall g \tag{18}$$

$$\gamma w_i x_{i\ell} \le NCT_{i\ell} Cap^{CT} \qquad \forall i,\ell \tag{19}$$

$$\gamma w_i z_{ij} \le NCL_{ij} Cap^{CT} \qquad \forall i, j \tag{20}$$

$$\lambda w_i h_{ir} \le NCR_{ir} Cap^{CT} \qquad \forall i, r \tag{21}$$

$$u_{\ell jq} \le NTL_{\ell jq} Cap^{ST}_{q} \qquad \forall \ell, j, q \tag{22}$$

$$\alpha . u_{\ell jq} \le NTL_{\ell jq} VCap^{ST}_{q} \qquad \forall \ell, j, q \tag{23}$$

$$\beta(\lambda w_i h_{ir}) \le NRC_{ri} Cap^{TR} \qquad \forall r, i \tag{24}$$

$$(1-\beta)(\lambda w_i h_{ir}) \le NRC_{ri} Cap^{CT} \qquad \forall r, i \tag{25}$$

$$\begin{array}{l} y_{jk}, \mathrm{v}_{\ell p}, \omega_{ro}, z_{ij}, x_{i\ell}, h_{ir} \in \{1,0\}; \quad u_{\ell jq} \ge 0; \\ NCL_{ij}, NCT_{i\ell}, NCR_{ir}, NTL_{\ell jq}, NRC_{ri} \ge 0 \text{ \& Integer} \end{array} \qquad \forall i, j, \ell, k, p, r, o, q \tag{26}$$

The first objective function is expressed with Equation 1 and minimizes the following costs:

- The cost of establishing and operating a non-recyclable MSW transfer station with technology p at location ℓ. This cost consists of a fixed construction cost and a variable operation cost that depends on the annual volume of compressed MSW to be generated.

- The cost of establishing and operating a landfill with technology k at location j. This cost consists of a fixed construction cost and a variable operation cost that depends on the annual volume of MSW to be received from transfer stations and population centers.
- The cost of establishing and operating a recycling plant with technology o at location r. This cost consists of a fixed construction cost and a variable operation cost that depends on the annual volume of recyclable MSW to be processed.
- The revenue from the sale of recycled materials, which should be deducted from the costs. Note that $\beta\%$ of recycled material will be sold and the rest will be used to promote the operation.
- The cost of transporting the non-recyclable MSW from population center i to transfer stations ℓ (by collection trucks).
- The cost of transporting the non-recyclable MSW from population center i to landfills j (by collection trucks).
- The cost of transporting the compacted MSW from transfer station ℓ to landfill j by semi-trailer trucks with technology q.
- The cost of transporting the recyclable MSW from population center i to recycling plant r (by collection trucks). Note that in this route collection trucks travel the distance $2d_{ir}$ because they not only transport the recyclable MSW from population center i to recycling plant r but also haul the promotional products in the opposite direction.
- The cost of transporting the sellable recycled materials from recycling plants to population centers (by transport trucks).

The second objective function is expressed with Equation 2 and minimizes the following GHG emission:

- The annual emission resulting from transfer station with technology p at location ℓ.
- The annual emission resulting from landfill with technology k at location j.
- The annual emission resulting from recycling plant with technology o at location r.
- The annual emission resulting from transport of non-recyclable MSW from population center i to transfer station ℓ (by collection trucks).
- The annual emission resulting from transport of non-recyclable MSW from population center i to landfill j (by collection trucks).
- The annual emission resulting from transport of compacted MSW from transfer station ℓ to landfill j by semi-trailer trucks with technology q.

- The annual emission resulting from transport of recyclable MSW from population center i to recycling plant r (by collection trucks). Like in the first objective function, trucks of this route travel the distance $2d_{iji}$.
- The annual emission resulting from transport of sellable recycled materials from recycling plant r to population center i (by transport trucks).

The third objective function is expressed with Equation 3 and minimizes the maximum of visual pollution due to MSW handling and processing facilities. This equation is obtained by assuming that visual pollution at a given location has a direct correlation with the amount of MSW processed by the facility and an inverse correlation with the square of its distance from the facility. So in each facility the more inflows exist and the closer it is to population center, the greater will be its visual pollution. Multiplier w_i represents the effect of population size in each area. Note that equation 3 is non-linear, and its linear form is expressed with equation 27 and constraint 28.

$$\text{Minimize}\ FPDI \tag{27}$$

$$w_i \left[\sum_{j} \frac{\phi^L \left(\sum_{i'} \gamma w_{i'} z_{i'j} + \sum_{\ell} \sum_{q} u_{\ell jq} \right)}{\left(d_{ij} + \varepsilon\right)^2} + \sum_{\ell} \frac{\phi^T \left(\sum_{i'} \gamma w_{i'} x_{i'\ell} \right)}{\left(d_{i\ell} + \varepsilon\right)^2} + \sum_{r} \frac{\phi^R \left(\sum_{i'} \lambda w_{i'} h_{i'r} \right)}{\left(d_{ir} + \varepsilon\right)^2} \right] \le FPDI \tag{28}$$

Constraints 4, 5, 6, and 7 limit the emissions of population centers, transfer stations, recycling plants, and landfills to the standards specified by government regulations.

Constraints 8, 9, 10, and 11 ensure that materials cannot be transported to a facility that does not exist (has not been established).

Constraint 12 guarantees that there is always only a single ultimate destination, meaning that each population center i has exactly one route to transport non-recyclable MSW to landfill j; a route which is either direct or indirect (via a transfer station).

Constraint 13 states that recyclable MSW in each population center must be allocated and transported to one of the existing recycling plants.

Constraint 14 maintains the balance of flow in transfer station at location ℓ. According to this constraint, outflow of transfer station toward landfill (the left side of equation) equals the sum of all inflows to that station.

Constraints 15, 16, and 17 maintain the capacities of transfer station with technology p at location ℓ, landfill with technology k at location j, and recycling plant with technology o at location r. In other words, the flow into each facility cannot exceed its available capacity. Note that when a facility does not exist, the right side of equation will be zero and there will be no flow into that facility.

Constraint 18 states that there can be no more than 1 facility at each candidate location. For the locations that can be used only as landfill we define $v_{gp} = 0$ and $w_{go} = 0$; for the locations that can be used only as transfer station we define $y_{gk} = 0$ and $w_{go} = 0$; and for the locations that can be used only as recycling plant we define $v_{gp} = 0$ and $w_{go} = 0$. ($\forall j, k$)

Constraint 19 computes the number of collection trucks required to transport non-recyclable MSW from population center i to transfer station ℓ (in terms of load-carrying capacity).

Constraint 20 computes the number of collection trucks required to transport non-recyclable MSW from population center i to landfill j (in terms of load-carrying capacity).

Constraint 21 computes the number of collection trucks required to transport recyclable MSW from population center i to recycling plant r (in terms of load-carrying capacity).

Constraints 22 and 23 compute the required number of semi-trailer trucks with technology q to transport compacted MSW from transfer station ℓ to landfill j (in terms of load-carrying and volume-carrying capacity respectively).

Constraint 24 computes the number of transport trucks required to transport sellable recycled materials from recycling plant r to population center i (in terms of load-carrying capacity).

Constraint 25 computes the number of collection trucks required to transport recyclable MSW from population center i to recycling plant r according to the amount of promotional products that must be hauled from recycling plant r to population center i (in terms of load-carrying capacity)

Finally, Constraint 26 expresses the type of decision variables. Note that all location and flow variables, except the ones relating to transfer station-landfill flow, are binary. Also, the variables expressing the number of vehicles should be integer.

2.2. Robust model

Considering the importance of addressing the issue of uncertainty in MSW management optimization problems, this study tackles this issue by adopting a robust optimization approach. Given the dependence of main cause of MSW generation, namely consumption, on economic factors such as prices, income and social welfare, cultural factors such as consumerism, and the general condition of society in each time frame, one viable approach to deal with uncertainty is the scenario-based analysis relying on forecast of parameters such as the quantity of recyclable and non-recyclable MSW produced per costumer per year. Thus, considering the discrete and scenario-based nature of our data, we use the model of Aghezzaf et al. (2010), which has been derived from the optimization model Mulvey et al. (1995), for our analysis. The general form of Aghezzaf's robust optimization model for minimization problems is expressed as Equation 29:

$$\text{Minimize}\, Z^R = \eta . \max_{s\in\Omega} (\xi_s - \xi_s^*) + \bar{\lambda} . \sum_{s\in\Omega} pr_s \xi_s \tag{29}$$

Where ξ_s is the objective function value under scenario $s \in \Omega$, ξ_s^* is the optimal value obtained by solving the deterministic model under scenario $s \in \Omega$, and pr_s is the probability of scenario $s \in \Omega$. As can be seen, the first part of equation 29 minimizes the maximum deviation from the optimal solution of deterministic model, and the second part of this equation minimizes the expected value of the objective function. Weights η and $\bar{\lambda}$ reflect the user's preferences and must be set accordingly. To do so, a user wishing to have a lower variability and greater expected cost should increase the value of η, and vice versa.

In general, the reasons behind choosing this approach are as follows:

- Considering the presence of discrete and scenario-based data, robust optimization model is used to model the problem.
- In this approach, the solution is feasible as long as uncertainty value is within the boundaries of uncertainty set. Given the strategic nature of the problem, this feature improves the investor confidence by expressing that the solution obtained from robust optimization approach is very likely to be realized.
- Robust optimization approach introduces less computation complexity to the models than do the other approaches of dealing with uncertainty.

In addition to the assumptions of deterministic model, our nondeterministic model takes the following assumptions.

- The amount of non-recyclable MSW generated (in ton per year) by each customer is an indeterminate parameter and its value varies with scenario.
- The amount of recyclable MSW generated (in ton per year) by each customer is an indeterminate parameter and its value varies with scenario.

- Because of the uncertain nature of parameters, a portion of non-recyclable and recyclable MSW generated in population centers may remain uncollected. In this case, the organization in charge of collection will be penalized by a value that represents the cost of using a new operator to address the shortcomings under special circumstances.

According to equation 29, the robust objective function is in the form of equation 30. The rest of constraints are rewritten based on nondeterministic variables and parameters.

$$\begin{aligned}\text{Minimize } Z^R = {} & \eta.\max_{s\in\Omega}\left[(\chi_1.Z_C^S+\chi_2.Z_P^S+\chi_3.Z_V^S)-(\chi_1.Z_C^S+\chi_2.Z_P^S+\chi_3.Z_V^S)^*\right] \\ & +\bar{\lambda}.\sum_{s\in\Omega} pr_s.(\chi_1.Z_C^S+\chi_2.Z_P^S+\chi_3.Z_V^S) \\ & +\kappa.\sum_{s\in\Omega}\sum_i pr_s.\delta_i^s+\zeta.\sum_{s\in\Omega}\sum_i pr_s.\tau_i^s\end{aligned} \tag{30}$$

Subject to:

$$\sum_i\sum_\ell \ddddot{TRP}\; NCT_{i\ell}^s d_{i\ell}+\sum_i\sum_j \ddddot{TRP}\; NCL_{ij}^s d_{ij}+\sum_i\sum_r \ddddot{TRP}\; NCR_{ir}^s d_{ir}\le MP^C \qquad \forall s \tag{31}$$

$$\sum_\ell\sum_p TP_p v_{\ell p}+\sum_\ell\sum_j\sum_q \widehat{TRP}_q\; NTL_{\ell jq}^s d_{\ell j}\le MP^T \qquad \forall s \tag{32}$$

$$\sum_j\sum_k LP_k y_{jk}\le MP^L \tag{33}$$

$$\sum_r\sum_o RP_o\omega_{ro}+\sum_r\sum_i \overline{TRP}\; NRC_{ri}^s d_{ir}+\sum_i\sum_r \ddddot{TRP}\; NCR_{ir}^s d_{ir}\le MP^R \qquad \forall s \tag{34}$$

$$z_{ij}^s\le\sum_k y_{jk} \qquad \forall i,j,s \tag{35}$$

$$x_{i\ell}^s\le\sum_p v_{\ell p} \qquad \forall i,\ell,s \tag{36}$$

$$h_{ir}^s\le\sum_o\omega_{ro} \qquad \forall i,r,s \tag{37}$$

$$\sum_\ell\sum_q u_{\ell jq}^s\le\psi\sum_k y_{jk} \qquad \forall j,s \tag{38}$$

$$\delta_i^s=\gamma^s(w_i)-\sum_j\gamma^s(w_i)z_{ij}^s-\sum_\ell\gamma^s(w_i)z_{i\ell}^s \qquad \forall i,s \tag{39}$$

$$\tau_i^s=\lambda^s(w_i)-\sum_r\lambda^s(w_i)h_{ir}^s \qquad \forall i,s \tag{40}$$

$$\sum_q\sum_j u_{\ell jq}^s=\sum_i\gamma^s w_i x_{i\ell}^s \qquad \forall \ell,s \tag{41}$$

$$\sum_i\gamma^s w_i x_{i\ell}^s\le\sum_p Cap_{\ell p}^T v_{\ell p} \qquad \forall \ell,s \tag{42}$$

$$\sum_i\gamma^s w_i z_{ij}^s+\sum_\ell\sum_q u_{\ell jq}^s\le\sum_k Cap_{jk}^L y_{jk} \qquad \forall j,s \tag{43}$$

$$\sum_i \lambda^s w_i h_{ir}^s \le \sum_o Cap_{ro}^R \omega_{ro} \qquad \forall r,s \tag{44}$$

$$\sum_p \nu_{gp} + \sum_k y_{gk} + \sum_o \omega_{go} \le 1 \qquad \forall g \tag{45}$$

$$\gamma^s w_i x_{i\ell}^s \le NCT_{i\ell}^s Cap^{CT} \qquad \forall i,\ell,s \tag{46}$$

$$\gamma^s w_i z_{ij}^s \le NCL_{ij}^s Cap^{CT} \qquad \forall i,j,s \tag{47}$$

$$\lambda^s w_i h_{ir}^s \le NCR_{ir}^s Cap^{CT} \qquad \forall i,r,s \tag{48}$$

$$u_{\ell jq}^s \le NTL_{\ell jq}^s Cap_q^{ST} \qquad \forall \ell,j,q,s \tag{49}$$

$$\alpha . u_{\ell jq}^s \le NTL_{\ell jq}^s VCap_q^{ST} \qquad \forall \ell,j,q,s \tag{50}$$

$$\beta(\lambda^s w_i h_{ir}^s) \le NRC_{ri}^s Cap^{TR} \qquad \forall r,i,s \tag{51}$$

$$(1-\beta)(\lambda^s w_i h_{ir}^s) \le NRC_{ri}^s Cap^{CT} \qquad \forall r,i,s \tag{52}$$

$$\begin{array}{l} y_{jk}, \nu_{\ell p}, \omega_{ro}, z_{ij}^s, x_{i\ell}^s, h_{ir}^s \in \{1,0\}; \quad u_{\ell jq}^s, \delta_i^s, \tau_i^s \ge 0; \\ NCL_{ij}^s, NCT_{i\ell}^s, NCR_{ir}^s, NTL_{\ell jq}^s, NRC_{ri}^s \ge 0 \text{ \& Integer} \end{array} \qquad \forall i,j,\ell,k,p,r,o,q,s \tag{53}$$

In the above model, equation 30 shows the robust form of the objective function. The first part of this equation minimizes the deviation of solution of each scenario from the optimal deterministic solution under that scenario with weight η; the second part of this equation minimizes the expected value of the objective function; and the third and fourth parts of the equation minimize the penalty of failing to collect non-recyclable and recyclable MSW respectively. It is also assumed that failing to collect MSW imposes an addition cost due to use of external contractors and the need for overtime work in facilities.

Constraints 39 and 40 compute the amount of uncollected non-recyclable and recyclable MSW respectively. Note that in the robust model, these constraints replace constraints 12 and 13 of the deterministic model.

The rest of constraints have the same definitions that were previously explained for deterministic optimization model, except that they are rewritten based on nondeterministic variables and parameters. Figure 2 shows the steps for the robust model solving process.

****Figure 2****

3. Case study

Tehran, the largest city and capital of Iran, with a large population, about 13,278,000, is located on the north of Iran, south of Alborz Mountains and 1190 m above sea level. It is ranked 23th by the population and 16th by the density (people per sqKm) in the world. Tehran's population and importance grew greatly in 20th century and today it is one of the major cities of the Middle East. Therefore, because of its steadily growing population, the city’s future MSW handling and management is a major concern. The main challenge of Tehran’s MSW management system is the large quantity of daily generated MSW that must be collected and disposed. Meanwhile, a large percentage of recyclable MSW is also collected and disposed along with non-recyclable waste. However, when segregated and collected properly, this waste can be recycled and sold in order to earn significant revenue. Figure 3 illustrates the amount of waste that has been generated in Tehran in recent years.

****Figure 3****

As can be seen, from 1997 to 2013, the size of Tehran’s MSW generation has had increased at a steady rate, thus, likely difficulty of handling future MSW generation volumes can be expected to cause adverse effects such as decreased urban hygiene, increased rate of contamination and resulting diseases, increased vermin population, etc. Thus, given the outdated technology and operations of Tehran’s MSW recycling and disposal facilities, there is an absolute need to invest in newer facilities.

To demonstrate the performance of the proposed model, it was utilized in a case study to determine the proper collection, recycling and disposal system for 22 districts of Tehran. We considered 5 of the 11 transfer stations currently existing in the study area as potential locations for the construction of a new transfer station and recycling plant. At the time of study, MSW of the study area was being disposed in two landfills located in Abali and Kahrizak regions, which we considered to remain unchanged. Figure 4 shows the location of candidate sites and landfills.

****Figure 4****

Also, 22 districts of Tehran with different population are shown in Figure 5.

****Figure 5****

To redesign the traditional MSW management system, we considered the establishment of landfills with one of the two available technologies, establishment of transfer stations with one of the two available technologies, establishment of recycling plants with one of the three available technologies, and use of semi-trailer trucks based on one of the three available technologies explained in the Appendix. The costs and other parameters also are given in the Appendix. Important details regarding the assumptions and modeling procedure are stated as follows.

- Distances between the candidate points, landfills, and regions have been determined in Table 6 based on the nearest distance between each pair. Although, Euclidean distance also could have been used.
- Types of technologies which are considered for semi-trailer trucks have been defined based on combination of a specific truck and trailer type; therefore, they can have different transfer costs, GHG emissions, load-carrying capacities, and volume-carrying capacities.
- Technologies which are defined for each facility, are the candidate technologies which can replace current technology in long-term planning of Tehran's MSW management system.
- Visual pollution factor related to each facility has been determined based on questionnaires which are completed by people living in regions.
- The population of each population center has been considered in Table 9 according to the latest population census that has been taken.
- In Table 10, four possible scenarios are defined for generation of recyclable and non-recyclable MSW based on general condition of society in future time.
- The weights of the objective function have been determined according to the decision maker opinions.

Since in this study, three objective functions, costs, GHG emissions and visual pollution, are considered and every objective has its own specific measures and units, to solve the problem and modeling objective function in robust form, LP Metric approach has been used. In this method, the distances between objectives and their optimum values are minimized. In order to consider all the objectives in the form of a single and dimensionless equation, they will be divided by their change intervals. Another point that should be considered is that the robust model provides the results in two stages. In other words, first, the decision variables related to facilities location (the location of each facility and the used technology) have been determined and then, in the second stage, others have been determined according to defined scenarios. This feature ensures that after the establishment phase of the facilities, in relation to the allocations, according to the occurred scenario, more efficient decisions are taken.

According to aforementioned assumptions, the robust model was coded in GAMS software v.24.0.1, and was run on a PC with corei7@ 2.0 GHz processor and Windows 7-64-bit OS. The results were obtained after 13 seconds of processing. The results of optimal location of facilities and allocation of each region, under each scenario, are shown in figures 6 and 7.

****Figure 6****

****Figure 7****

4. Discussion

As can be seen in Figures 6 and 7, regarding the effects of constraints and assumptions on the results of the proposed model, the following remarks can be made:

- In case of allocation of one area to a facility of MSW disposal and recycling system, that facility is considered already built.
- Each population area can dispatch its non-recyclable waste to the landfill either directly or through one of the transfer stations.
- Each population area sends its recyclable waste to one of the recycling centers.
- Each candidate site can house at most one facility.

As can be seen in Figure 6, in the first result stage of the robust model, transfer stations have been established in the candidate points 1, 4, and 5 and recycling plants in candidate points 2 and 3. These results will be same for all possible scenarios, while allocation decision variables regarding the amount of recyclable and non-recyclable waste generated by each person will be different. Another important point is that the first objective function, which is try to minimize the total cost, establishes the facilities close to more populous areas as much as possible but the third objective function, which is try to minimize the visual pollution, establishes the facilities away from more populous areas as much as possible. As can be seen, the results have average behavior because of considering 3 objectives, cost, GHG emission, and visual pollution, simultaneously. Also, some analysis can be performed on allocation variables. For example, as can be seen in Figure 6, in scenario 2 with the greatest amount of non-recyclable and lowest of recyclable waste, 14 regions directly send their waste to landfills 6 and 7, while in other scenarios more regions firstly send their waste to transfer stations. Region 4, the most populous region, in scenario 1, scenario 2, and scenario 4 directly send its waste to one of the landfills, while region 22, the least populous region, only in scenario 3 send its waste to landfills, directly.

To allow a better decision to be made based on the presented results, decision maker must be provided with a set of Pareto solutions. One way of doing so is to use the weighted sum method, in which a variety of result can be obtained by altering the weights of different objective functions. Table 2 shows the different weights that are randomly generated to show the impact of them on objective functions and also the tradeoff between objectives. Thus, the model was solved under the first scenario using this approach and the results were organized as presented in the following.

****Table 2****

As can be seen, using different weights result in different solutions and ultimately different objective function values. To observe the behavior of objective functions together, in Figure 8, all solutions are plotted in ascending order of total cost objective function value.

****Figure 8****

As can be inferred from Figure 8, an increase in total system cost corresponds to an increase in GHG emission and vice versa. In other words, there is a direct (positive) relationship between the cost and GHG emission objective functions. On the other hand, an increase in total system cost corresponds to a decrease in visual pollution function value and vice versa, which means there is an inverse (negative) relationship between the cost and visual pollution objective functions. It can therefore be concluded that an increase in GHG emission also corresponds to a decrease in visual pollution and vice versa. Thus, it is obvious that to reduce the visual pollution, waste disposal and recycling facilities have to be built far away from existing population areas, which of course translates into longer travels for MSW hauling vehicles and therefore higher total system cost and GHG emission. This conflict between the objectives highlights the essential role of multi-objective optimization, which allows the decision makers to weigh the tradeoff between the objectives and plan the system according to case-specific purposes.

As mentioned earlier, in the proposed model, the parameters γ and λ, i.e. the non-recyclable and recyclable waste generation per capita, are considered uncertain (indeterminate) parameters used in robust modeling approach to enhance the design of MSW management and disposal system. Also, these two parameters are a function of factors such as income level, welfare level, general state of society, etc., thus, this section discusses the effect of these parameters on the objective functions, namely the total cost, the GHG emission, and the visual pollution. Since Scenario 1 is the most likely scenario for the case study, γ and λ values are assumed to be 0.0333 and 0.373, respectively. After solving the proposed model deterministically for Scenario 1, variations in values of objective functions resulting from ±90% change in γ and λ were determined. These variations are presented in Tables 3 and 4.

Table 3

Table 4

It can be seen that as γ and λ values increase, so do the total cost, the GHG emission, and the visual pollution. But in this case, γ values beyond 0.04662 and λ values beyond 0.5222 result in infeasible solutions. In other words, the deterministic model can only respond to a certain range of change in γ and λ. Figures 9 and 10 and 11 illustrate the effects of γ and λ values on the total cost, the GHG emission, and the visual pollution, respectively.

Figure 9

Figure 10

Figure 11

As can be seen, any change in γ and λ can have substantial effects on the objective function values and thus the model solutions. The changes caused by λ however are far more profound than those due to γ. These figures also show that some changes in γ and λ cause sharp and sudden jumps in the objective function values, which can be attributed to construction and activation of new MSW disposal and recycling facilities in the solution, leading to a sharp increase in the total costs, the GHG emission and the visual pollution. The main advantage of the presented robust model is its ability to minimize the effects of γ and λ variations on the results of analysis, and thereby maintain the feasibility and quality of solutions. In Table 5, the results of the proposed robust model and the deterministic models are compared.

Table 5

In this table, each row represents a model considered for the design of MSW management system and each column represents the scenario occurred after system implementation. As can be seen, in the case of considering the deterministic model for scenario 1, the model provides an acceptable solution for every possible (probabilistic) scenario. Note that in scenario 1, γ and λ are at their peak values, and since the actual values are always lower than these values, the solutions of the model will always be feasible. In this case, for scenario 1, the deterministic model provides better solutions (objective function values) than the robust model, but for other scenarios, the presented robust model yields better solutions in terms of every objective. In the case of considering the deterministic model for scenario 2, if scenarios 2 and 4 (where the actual values of γ and λ are less than or equal to γ and λ values considered in scenario 2) occur, the deterministic model provides acceptable solutions, but can outperform the robust model only in scenario 2. In this case, the results of deterministic model are not valid for scenarios 1 and 3. The same results are observed in the case of considering the deterministic model for scenario 3. In the case of considering the deterministic model for scenario 4, the results will be acceptable only in the case of scenario 4.

It can therefore be concluded that considering the multitude of factors involved in values of γ and λ and ultimately the results of the model, consistent quality and sometime feasibility of the solutions provided by the deterministic model is doubtful. As Table 1 shows, the majority of previous models in the context of MSW disposal system are deterministic (see, Alumur & Kara, 2007; Erkut et al., 2008; Rodrigues et al., 2012; Chatzouridis & Komilis, 2012; Ardjmand et al., 2014; Eiselt & Marianov, 2014a; Eiselt & Marianov, 2014b; Asefi et al., 2015; Jabbarzadeh et al., 2016; Yu & Solvang, 2016; Lyeme et al., 2017). Hence, there is a need for new models capable of providing not merely feasible but high quality solutions under uncertainty. In this regard, the use of robust approach for the design of MSW management system can limit the effect of uncertainties on the quality and feasibility of the solutions. Another advantage of robust modeling over other uncertainty handling approaches is its ability to provide a specific solution for each scenario, thus allowing the system design to maintain a certain degree of flexibility vis-à-vis outcomes of every scenario. This is while other uncertainty handling approaches such as stochastic programming and chance-constrained programming such as

Xi et al. (2010) provide only one solution expressing a tradeoff between existing scenarios. In other words, neither deterministic models nor other uncertainty handling approaches are as flexible as robust model against the scenarios involving MSW collection, recycling, and disposal. Therefore, our proposed model covers all the drawbacks of previous models in the context of MSW disposal system.

5. Conclusion and future research

This paper presented a multi-objective optimization model for the design of MSW management system, in which real data pertaining to the city of Tehran was used in a case study to redesign MSW management system of this city. The proposed model is able to minimize the cost of MSW management system, its greenhouse gas emission, and visual pollution due to construction of MSW handling and processing facilities. During the past two decades, there have been tremendous efforts accomplished on location and allocation of MSW processing and disposal facilities and the present study has been an attempt to fill the gap in this area. In this study, the forms of "Min Max" and "Min Sum" have been considered for the objectives in a comprehensive framework in order to consider social justice among more populated regions (see, Ramos et al., 2014). In addition, by considering economic objective accompanied by environmental and social objectives, we may reach sustainable goals. Moreover, the proposed method has taken into account waste transfer stations, landfills and recycle plants simultaneously as a part of problem formulation, which helps us reach more comprehensive solutions. Also, it has been shown that if uncertainties in parameters were ignored, optimization models would not be able to reach proper solutions (While there are numerous deterministic model in the context of MSW disposal system). Hence, the present study has implemented robust approach of Aghezzaf et al. (2010) to tackle uncertainty associated with sensitive parameters, which helped us detect more robust solutions. Not only does the proposed robust model lessen the effects of variation in uncertain parameters, but in comparison with other similar methods such as stochastic programming, produces more flexible results. However, this is not the only method which could be used for handling uncertainty, there are other methods such as the one proposed by Bertsimas & Sim (2004) and Ben-Tal & Nemirovski (1998), which could be considered as an alternative strategies to investigate the problem. Another approach is to use Z-numbers (Zadeh, 2011) to handle the uncertainty with parameters and we leave it for interested researchers as future studies. Moreover, future studies could consider the routing problem for MSW collection and transport vehicles to make the model more realistic. In addition, the proposed model can be developed for storable wastes, allowing the process to be completed in forthcoming time periods. Also, to reduce the volume of MSW to be buried, model can be developed by giving consideration to the portion of MSW which can be recovered as energy in low-emission power plants that consume a percentage of MSW as feedstock.

Appendix

The cost, emission and other parameters are given in Tables 6-10.

****Table 6****

****Table 7****

****Table 8****

****Table 9****

****Table 10****

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Table1: Review of site-selection and capacity allocation optimization models for MSW facilities

Article	Type of formulation		Number of objective(s)		Type of objective(s)			Locating			Model	
	Min Sum	Min Max	Single- objective	Multi-objective	Cost (Economic)	Environmental	Social	Transfer stations	Landfills	Recycle plants	Deterministic	Nondeterministic
Alumur & Kara (2007)	✓			✓	✓				✓		✓	
Erkut et al. (2008)	✓			✓	✓	✓		✓	✓	✓	✓	
Xi et al. (2010)	✓		✓		✓				✓			✓
Rodrigues et al. (2012)	✓			✓	✓		✓				✓	
Chatzouridis & Komilis (2012)	✓		✓		✓			✓			✓	
Berglund & Kwon (2014)	✓		✓		✓				✓			✓
Ardjmand et al. (2014)	✓		✓		✓				✓	✓	✓	
Eiselt & Marianov (2014a)	✓			✓	✓	✓		✓	✓		✓	
Eiselt & Marianov (2014b)	✓			✓	✓	✓		✓	✓		✓	
Asefi et al. (2015)	✓		✓		✓			✓	✓	✓	✓	
Jabbarzadeh et al. (2016)	✓			✓	✓	✓		✓	✓		✓	
Yu & Solvang (2016)	✓			✓	✓				✓	✓	✓	
Lyeme et al. (2017)	✓			✓	✓	✓			✓	✓	✓	
Proposed model	✓	✓		✓	✓	✓	✓	✓	✓	✓		✓

Table 2: The tradeoff between the objectives according to different weights in weighted sum method

W_c	W_p	W_v	Z_c	Z_p	Z_v
0.1	0.1	0.8	7103023980.08	10635561.68	336098812822.02
0.3	0.5	0.2	7103020455.86	10635109.29	336099160295.82
0.2	0.5	0.3	7103019486.86	10635049.06	336099160295.82
0.3	0.3	0.4	7103021991.48	10635391.12	336099163461.31
0.2	0.7	0.1	7103022342.08	10635275.62	336098807221.53
0.3	0.1	0.6	7103020066.98	10635279.11	336099167844.30
0.1	0.4	0.5	7103021591.36	10635226.82	336098807465.03
0.4	0.4	0.2	7109595429.56	10650598.59	332097246691.56
0.8	0.1	0.1	7103115499.58	10643612.09	335898812822.02
0.2	0.2	0.6	7157513486.24	10767152.10	306087636458.82

Table 3: The sensitivity analysis based on γ

Percentage change	γ **(ton/year)**	**Objective function**		
		Total cost	**GHG emission**	**Visual pollution**
-90%	0.00333	7358722258.9	33797623.0	1165863746712.9
-80%	0.00666	7546726869.3	35711774.6	1318952093776.8
-70%	0.00999	7710926117.0	36076193.3	1319020900182.5
-60%	0.01332	7906201868.2	38089084.2	1712930812221.8
-50%	0.01665	8068670051.3	38467025.1	1713009096314.4
-40%	0.01998	8234303926.2	38855591.6	1713134212809.5
-30%	0.02331	8398182304.6	39141179.3	1713198943642.8
-20%	0.02664	8610369840.7	42043226.0	2363592545879.7
-10%	0.02997	8773416666.0	42461511.0	2363638448715.2
0%	0.03330	8939257165.5	42775434.5	2363727701408.0
+10%	0.03663	9321527315.6	55161888.7	4283687508119.3
+20%	0.03996	9484485098.1	55511896.5	4283745670090.3
+30%	0.04329	9649002063.5	55979950.1	4283838076276.9
+40%	0.04662	**	**	**
+50%	0.04995	**	**	**
+60%	0.05328	**	**	**
+70%	0.05661	**	**	**
+80%	0.05994	**	**	**
+90%	0.06327	**	**	**

** The model is Infeasible

Table 4: The sensitivity analysis based on λ

Percentage change	λ **(ton/year)**	**Objective function**		
		Total cost	**GHG emission**	**Visual pollution**
-90%	0.0373	2332396179.0	7737756.9	117107289624.4
-80%	0.0746	3050913332.9	11043984.2	233687124202.8
-70%	0.1119	3769676423.2	14371715.3	350266958781.3
-60%	0.1492	4754815103.8	17773525.3	630978535633.9
-50%	0.1865	5540243181.2	23871002.4	788580506979.7
-40%	0.2238	5927098889.7	24415682.5	790001330487.8
-30%	0.2611	6672456688.7	28476660.2	923743902688.8
-20%	0.2984	7427798020.8	33127943.2	1370762054578.4
-10%	0.3357	8205890764.0	38824650.6	2127442588964.2
0%	0.373	8939257165.5	42775434.5	2363727701408.0
+10%	0.4103	9913004685.2	59866065.0	4711901152752.3
+20%	0.4476	10664425192.0	65039271.2	5140148700988.0
+30%	0.4849	11424582798.1	70448458.1	5568425370630.1
+40%	0.5222	**	**	**
+50%	0.5595	**	**	**
+60%	0.5968	**	**	**
+70%	0.6341	**	**	**
+80%	0.6714	**	**	**
+90%	0.7087	**	**	**

** The model is Infeasible

Table 5: Comparing the results of robust model with deterministic models

Considered model	Objective	Occurrence			
		Scenario 1	Scenario 2	Scenario 3	Scenario 4
Deterministic model for scenario 1	**Cost**	9339257165.5	9339257165.5	9339257165.5	9339257165.5
	GHG emission	81175434.5	81175434.5	81175434.5	81175434.5
	Visual pollution	147727701408.0	147727701408.0	147727701408.0	147727701408.0
Deterministic model for scenario 2	**Cost**	**	8133827072.2	**	8133827072.2
	GHG emission		74529175.7		74529175.7
	Visual pollution		94503224298.1		94503224298.1
Deterministic model for scenario 3	**Cost**	**	**	8593352040.9	8593352040.9
	GHG emission			78925169.4	78925169.4
	Visual pollution			113137116327.0	113137116327.0
Deterministic model for scenario 4	**Cost**	**	**	**	7144091349.0
	GHG emission				63081762.9
	Visual pollution				72282093451.6
Proposed robust model	**Cost**	**9622202805.4**	**8373917659.3**	**9031660088.7**	**7943155507.4**
	GHG emission	**81420393.8**	**70175846.2**	**80501960.1**	**77577149.5**
	Visual pollution	**151912864466.1**	**100562421715.8**	**142261466007.5**	**86365440423.3**

** The model is Infeasible

Table 6: Distances between the candidate points, landfills, and regions (km)

	Candidate site 1	**Candidate site 2**	**Candidate site 3**	**Candidate site 4**	**Candidate site 5**	**Landfill 1**	**Landfill 2**
Region 1	2.4	18	31.8	29.8	10.1	45.5	28.7
Region 2	11.9	25.3	20.6	18.9	8.6	33.8	38.6
Region 3	5.2	14.7	24.5	27	7.5	38.2	28
Region 4	14.1	8.1	22.8	32.4	11.9	36.5	24.3
Region 5	16.4	27.3	20.7	15.2	8.4	33.9	40.5
Region 6	9.4	20.7	16.1	21.8	0.7	31.9	34
Region 7	8.9	19.8	18.8	25.9	5.4	37.5	33
Region 8	17.2	8.1	21.9	34.6	14.1	34.5	19.9
Region 9	21.6	30.8	10.2	24.7	12.2	22.8	44
Region 10	20.8	30	10.9	23.9	11.4	24.4	43.2
Region 11	20.3	28.9	8.2	30.3	12.2	24	37.4
Region 12	12.2	21.8	9.9	29.1	8	26.5	35
Region 13	19.8	14.7	15.2	35.9	15.4	28.9	26.1
Region 14	19.2	15.1	14	35.4	14.9	27.7	26.6
Region 15	26.5	18.7	10.7	44.7	22.2	23.3	30.1
Region 16	28.3	25.5	4	41.5	18.4	21.2	26.9
Region 17	22.4	33.3	7.7	28.5	14.3	20.3	47.6
Region 18	27.5	39.2	15	27.6	19.6	23.6	50.7
Region 19	23.5	30.1	2.1	38.3	19.1	16.4	41.5
Region 20	36	29.8	12.6	41.1	26.3	12	41.2
Region 21	28.3	38.9	24.9	15.8	20.8	33.5	52.1
Region 22	25.7	36.7	36.3	1.2	21.2	44.9	51
Landfill 1	45.5	36.5	16.4	44.9	31.9	-	-
Landfill 2	28.7	24.3	41.5	51	34	-	-

Table 7: Parameters related to municipal solid waste vehicles

	Collection truck	**Transport truck**	**Semi-trailer truck**		
			Technology A	**Technology B**	**Technology C**
Transfer cost ($/km)	32.6	12.75	16.3	12.75	15
GHG emission (g/km)	1.804	1.189	1.398	1.174	1.267
Load-carrying capacity (ton)	3	25	72	53	63
Volume-carrying capacity (m^3)	-	-	846	498	652

Table 8: Parameters related to municipal solid waste facilities

	Candidate site	Landfill		Transfer station		Recycle plant		
		Technology A	**Technology B**	**Technology A**	**Technology B**	**Technology A**	**Technology B**	**Technology C**
Fix cost ($)	**Site 1**	-	-	12500	22700	275000	292500	262000
	Site 2	-	-	25700	51300	337500	350000	325000
	Site 3	-	-	32500	43000	337500	362500	320000
	Site 4	-	-	43600	47500	165000	185000	157500
	Site 5	-	-	22800	45500	200000	240000	167500
	Landfill 1	82500	120000	-	-	-	-	-
	Landfill 2	87500	130000	-	-	-	-	-
Operational cost ($/ton)	**	3000	2650	300	150	4300	5800	5190
GHG emission (g/ton)	**	600	750	5200.5	1630	21000	16800	19500
Visual pollution factor	**	9	9	4	4	3	3	3
Capacity (ton/year)	**	830000	1000000	3700000	4200000	20600000	22300000	18300000
PRM_o ($/ton)	**	-	-	-	-	5440	5260	5300
Compacting (%)	**	-	-	7.2	7.2	-	-	-

** For all sites

Table 9: The population of the regions (people)

Region	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Population	439467	632917	314112	861280	793750	229980	309745	378118	158516	302852	288884
Region	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**
Population	240720	276027	484333	638740	287803	248589	391368	244350	340861	162681	128958

Table 10: The value of the uncertain parameters

Scenario	**1**	**2**	**3**	**4**
Probability	0.35	0.3	0.22	0.13
γ^s **(ton/year)**	0.0333	0.0333	0.0212	0.0212
λ^s **(ton/year)**	0.3730	0.3140	0.3730	0.3140

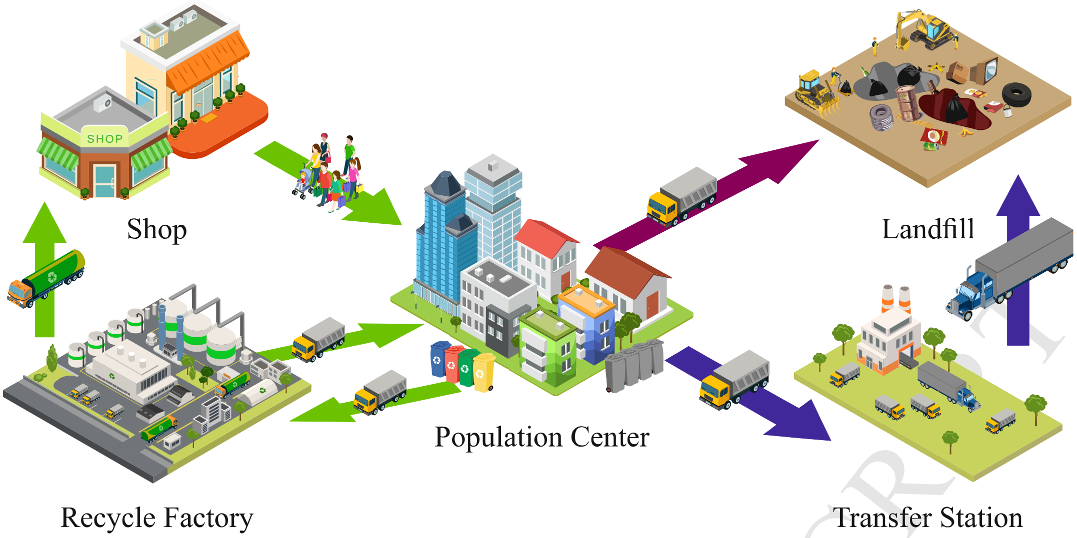


Figure 1: Overall structure of considered MSW system

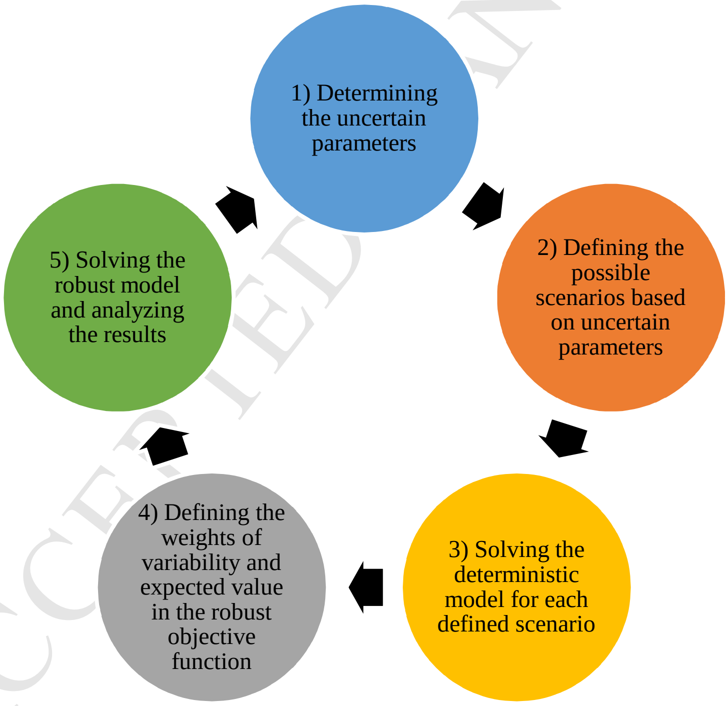


Figure 2: Robust model solving process

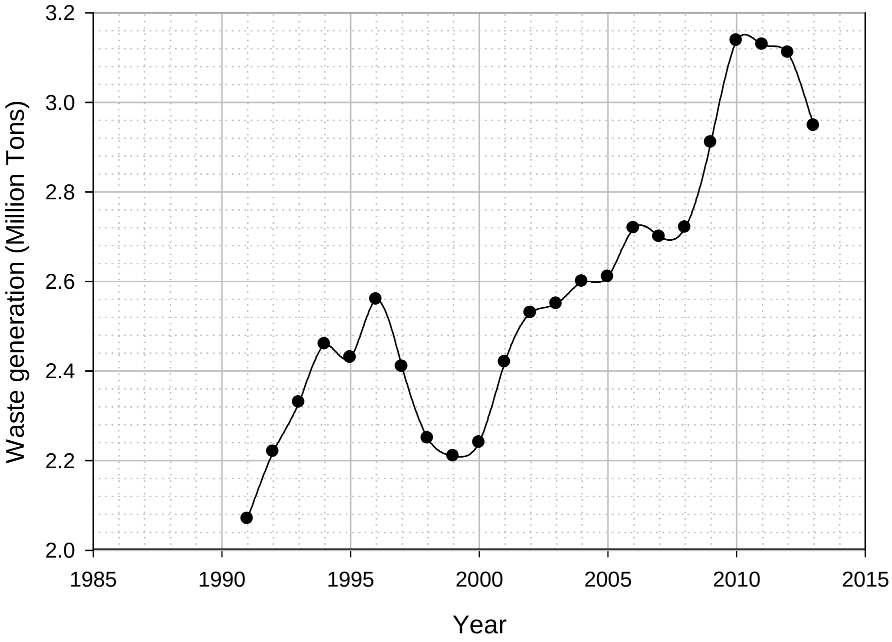


Figure 3: Amount of generated waste in Tehran in recent years

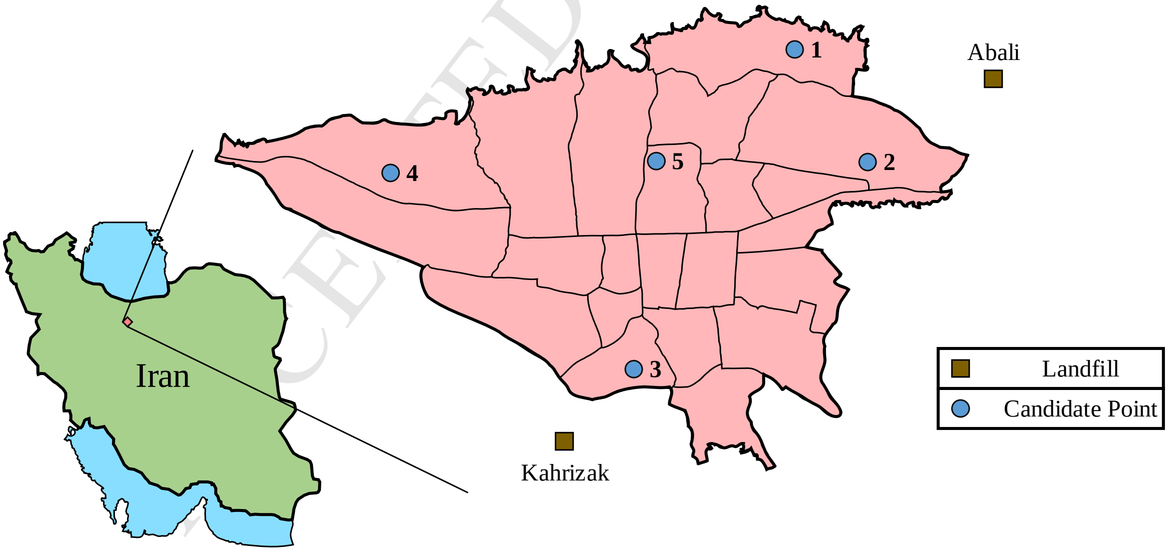


Figure 4: Location of candidate sites and landfills

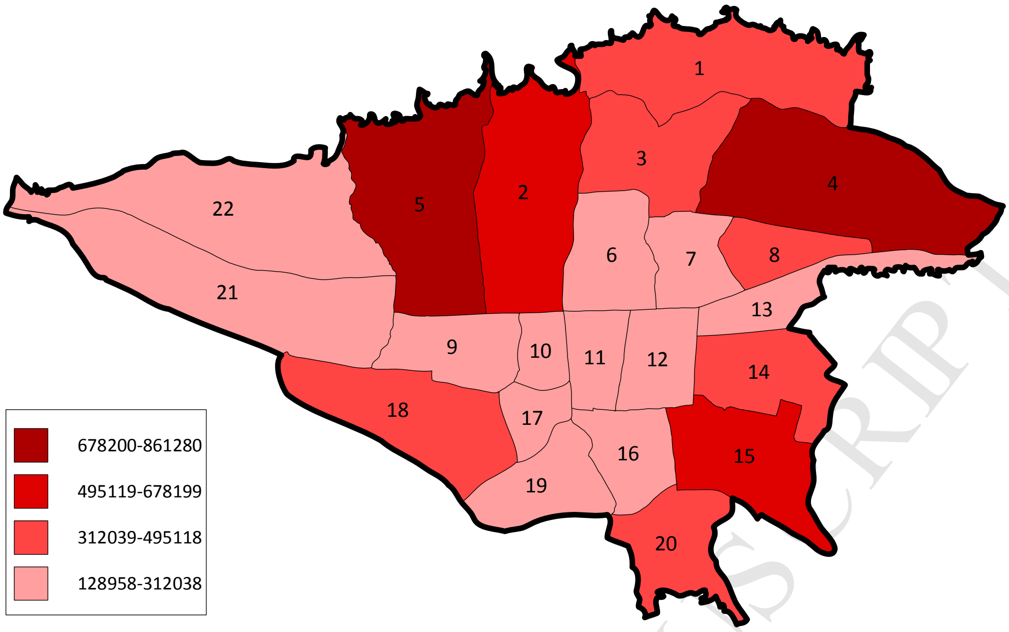
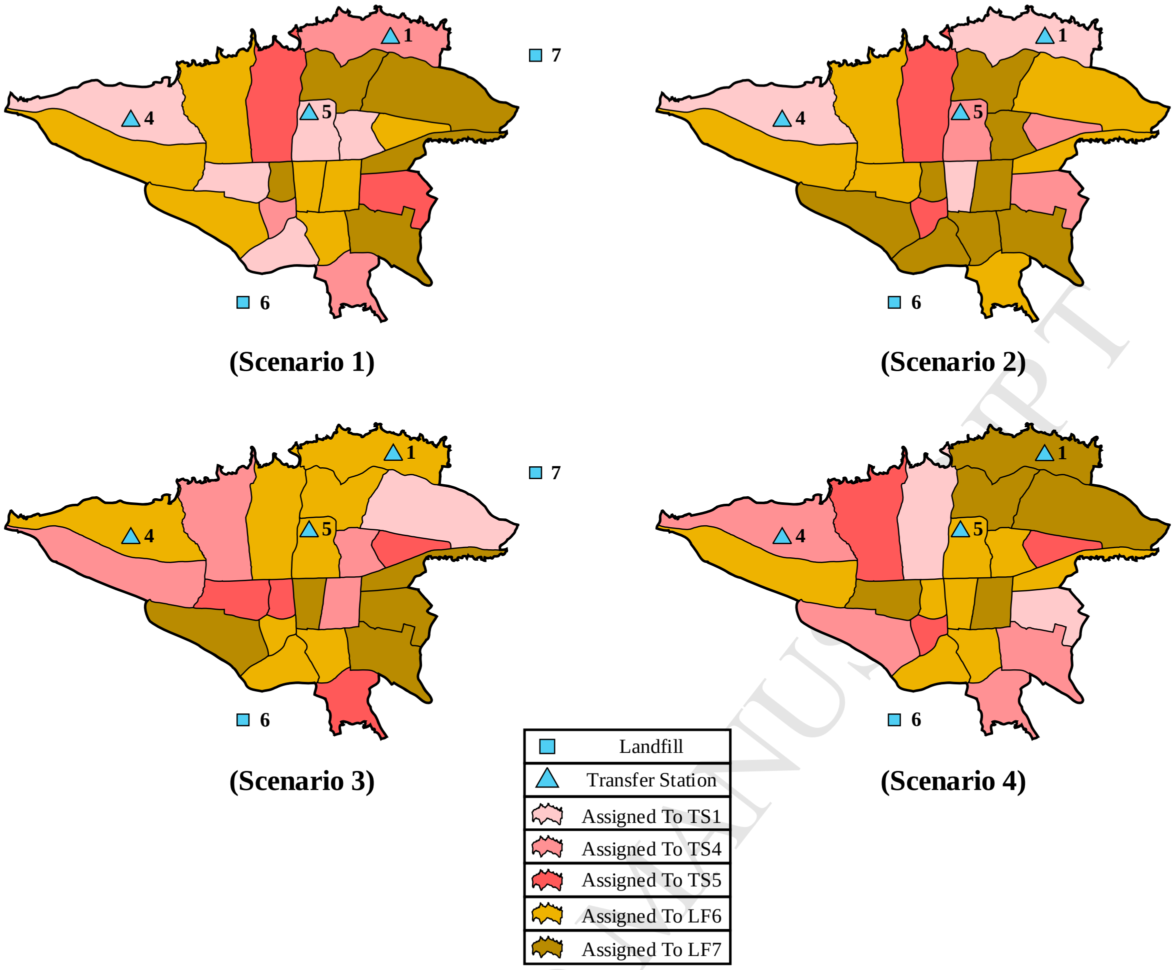


Figure 5: Districts of Tehran and their populations



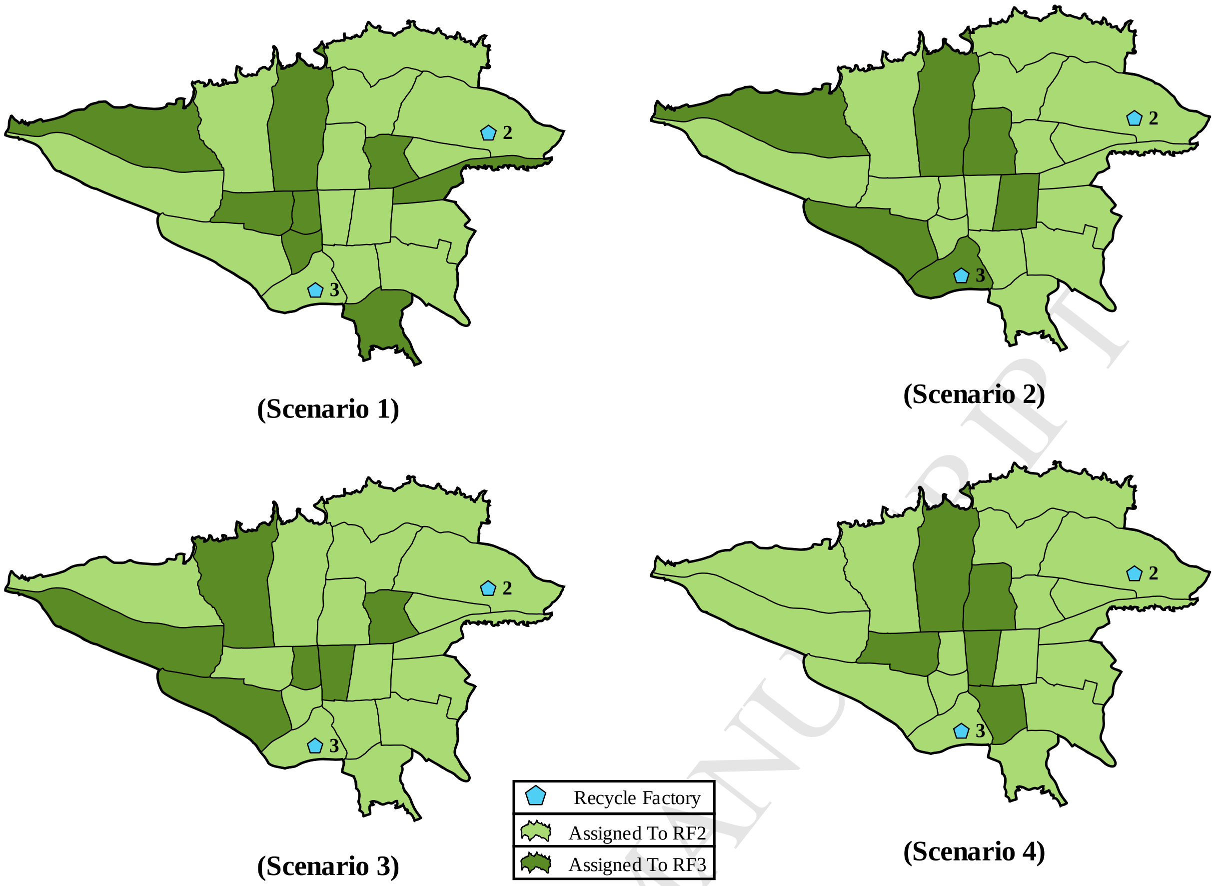
(Scenario 1)

(Scenario 2)

(Scenario 3)

(Scenario 4)

Figure 6: Optimal location of disposal facilities and allocation of regions for non-recyclable waste under each scenario



(Scenario 1)

(Scenario 2)

(Scenario 3)

(Scenario 4)

Figure 7: Optimal location of recycle plants and allocation of regions for recyclable waste under each scenario

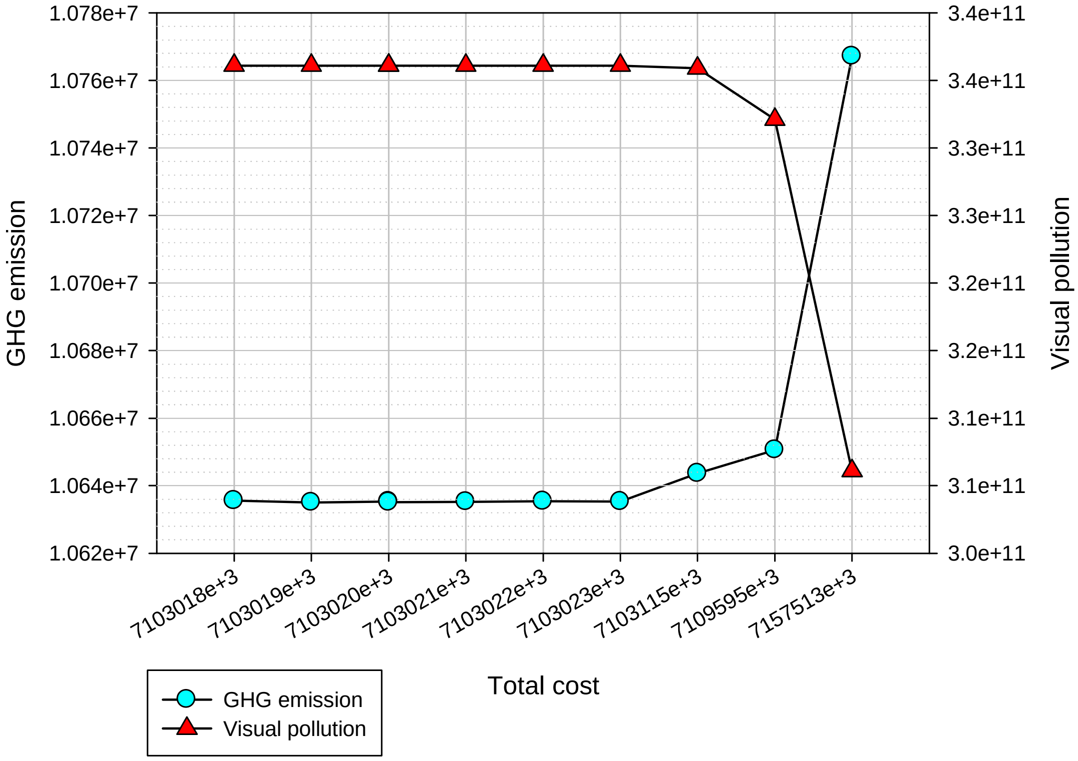


Figure 8: The tradeoff between objectives

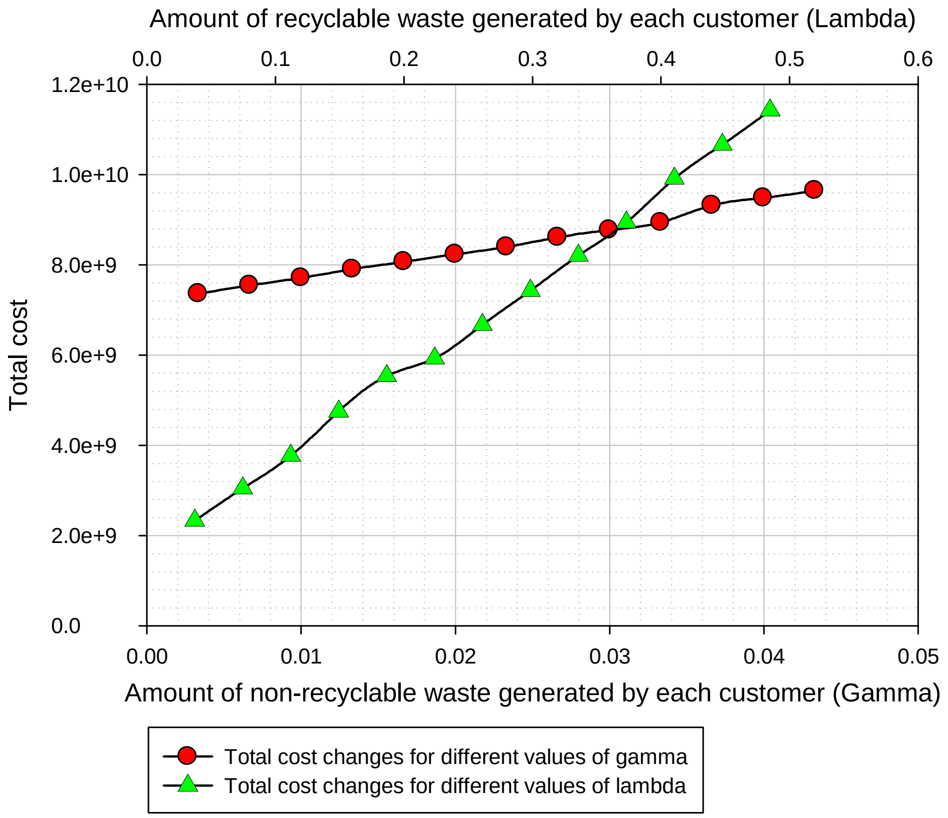


Figure 9: The sensitivity analysis on total cost

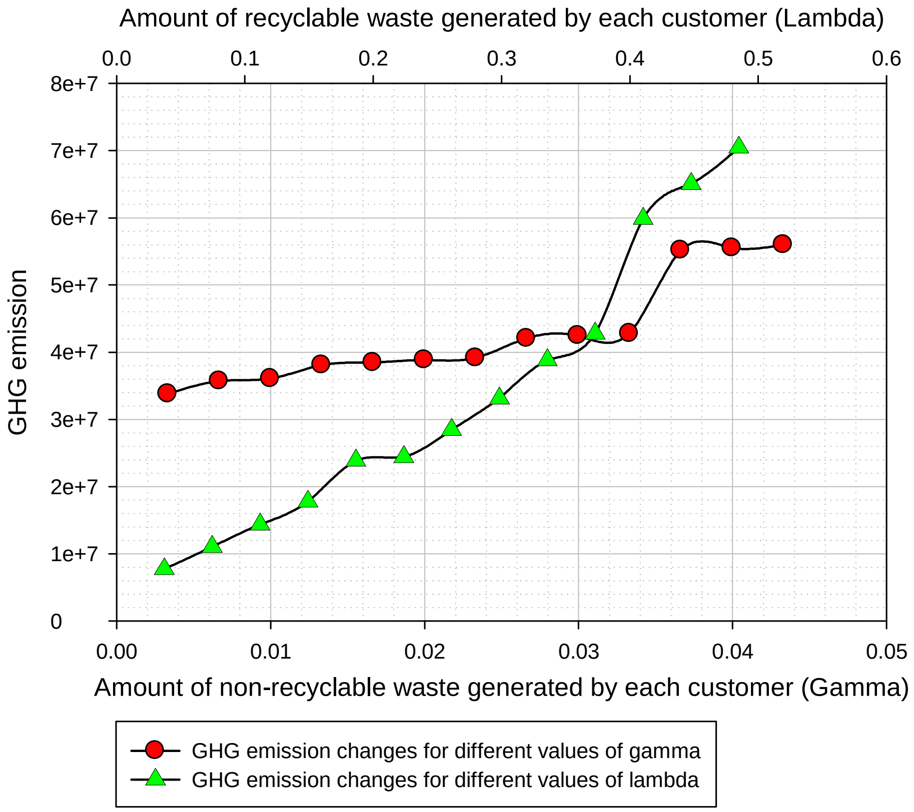


Figure 10: The sensitivity analysis on GHG emission

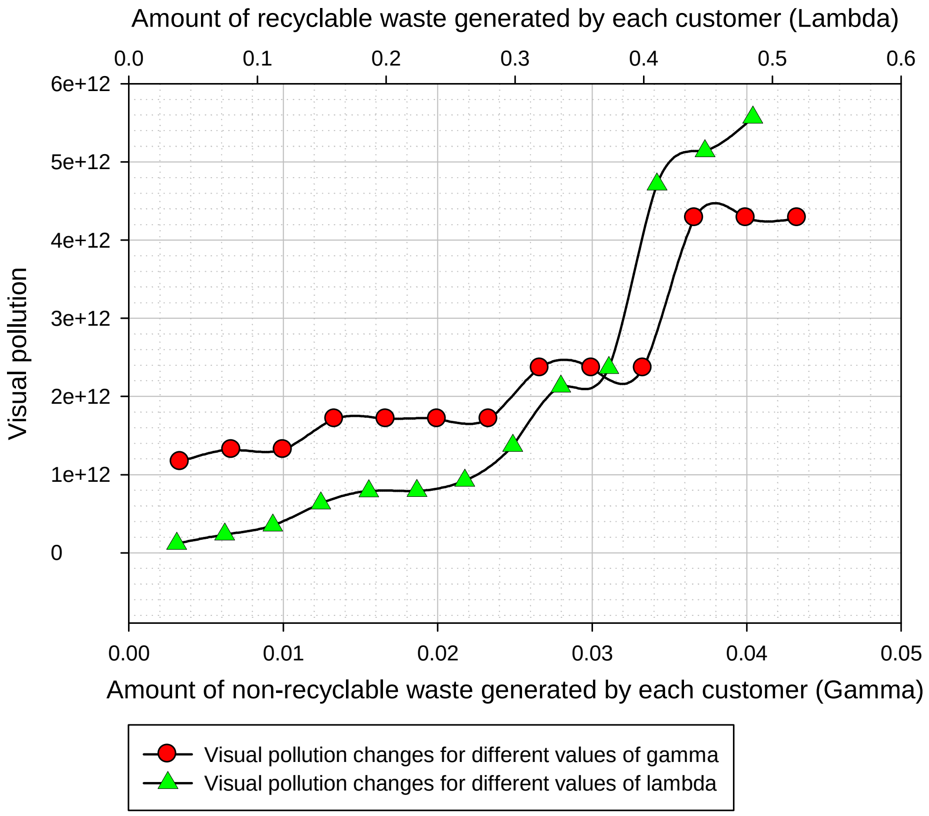


Figure 11: The sensitivity analysis on visual pollution

Highlights:

- Costs, GHG emission and visual pollution objectives are considered simultaneously.
- Make a sustainable assessment framework for municipal solid waste system.
- Making the problem realistic, amount of waste generation is considered uncertain.
- Deal with uncertainty by a robust optimization method.
- Employment of the proposed model in a real case study in Tehran, Iran.