Robust Possibilistic Programming Approach for Design of Tehran Municipal Solid Waste Management System

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Abstract

Decision-making about the location of the Municipal Solid Waste (MSW) system's facilities is one of the challenging issues in an urban area because of its considerable impacts on economy, ecology, and the environment. Also, since such strategic problems are tainted with great degree of uncertainty, this study proposes a bi-objective fuzzy mathematical programming model for design of a MSW management system by considering both economical and environmental aspects. A version of Robust Possibilistic Programming (RPP) approach i.e. RPP-II is used to handle the uncertain parameters of the problem. Applicability of the proposed model in practice is illustrated through the Tehran MSW system where determine the location and allocation of transfer stations as well as the appropriate waste compacting technology levels for these facilities.

Keywords:
Municipal solid waste, Robust possibilistic programming, Location-allocation problem, ε-constraint method

Introduction

Population growth, underlying economic development, urbanization, and the general trend towards the industrialization in the recent years have made Municipal Solid Waste (MSW) as the major environmental concern for urban communities particularly in developing countries [1].
The main goals of MSW management are protection of the human health, promotion of environment quality, and provision of support to economic productivity and sustainability [2]. Therefore, an inappropriate management of MSW system can lead to a drastic threat to the all components of environment as well as public health. The decision-making on MSW system involves the activities associated with site selection of the waste management system's facilities such as treatment and disposal facility, allocation of waste flows to these facilities, and determination of the transportation routes [3].
The management of MSW system is a serious challenging task for city planners throughout the world since it is essential to tackle with its conflicting objectives. Minimization of the total waste collection time while taking account of economic considerations were studied for a waste collection system of a zone in Municipality of Santiago by Arribas et at. [4]. To achieve the improvement in the initial state of this system, they applied a methodology comprised of three phases. Definition of the zones and vehicle fleet design based upon integer programming models and Geographic Information System (GIS) tools were obtained through the proposed methodology. Galante et al. [5] proposed an integrated approach for localization and capacity planning of transfer stations as well as determination of the number and type of collection vehicle fleet. Two conflicting objectives including the minimization of total costs and the minimization of adverse environmental impacts were considered in this study. Taking some assumptions in these studies can be closer them to real word applications [6].
Considering transfer stations in MSW management causes trade-offs between transportation costs and investment and operation costs of these facilities [7]. According to [8], a slightly improvement in the waste collection phase can lead to a substantial saving in the total costs. Transfer stations as intermediate facilities for processing and temporary deposition of wastes can play a substantial role in saving the collection costs. In the study that was done by Chatzouridis and Komilis [9], a practical approach based on binary programming and GIS tool was developed for determining the precise locations of the transfer stations, their capacity planning, and identification of optimal routes. The objective function of this study integrated the capital and operating costs associated with the system facilities and vehicles and transportation costs. In another study, Eiselt and Marianov [10] presented a bi-objective mixed-integer linear programming model in order to locate landfills and transfer stations and determine the dimension of each final facility. In addition to cost issues, minimization of pollution was formulated as second objective function in their model. Furthermore, they studied the issue of locating solid waste management facilities involved communal waste collection stations by the goal of minimization of the total distance travelled [11]. In addition to the issue of facility location, the model developed by Jabbarzadeh et al. [12] is capable of determining the required waste processing technology at each transfer station. Minimization of total costs, energy consumptions and greenhouse gas emissions are three objective functions of this study. To tackle with these conflicting objective functions, an interactive fuzzy programming solution approach were applied by the

authors.

Much of the decision-making in Municipal Solid Waste (MSW) management systems are often taken place in an environment with high degree of uncertainty in which neglecting the uncertainty of such systems in decision-making can lead to impose high risk to the system. Since describing the system parameters as deterministic values is not easy work, fuzzy mathematical programming has been applied extensively to deal with the objective functions and the constraints cannot be known precisely. The literature on the location-routing problem involves studies with fuzzy variables. With respect this fact that the demand of a customer is not known precisely until the vehicle reaches the customer, a location-routing problem with fuzzy demands proposed by Mehrjerdi and Nadizadeh [13]. In order to cope with the demand uncertainty, this problem was modeled with a fuzzy chance-constrained programming based upon fuzzy credibility theory. In another study, demand uncertainty along with the multi-period planning horizon were considered in a dynamic capacitated location-routing problem [14]. The work of Zarandi et al. [15] examined a location-routing problem under uncertainty of customers' demand and vehicle travel times. In this kind of problems, with respect to the NP-hard nature of the problem, fuzzy credibility theory has been used in parallel with some approximation algorithms to solve them. For example, Zarandi et al. [16] applied Simulated Annealing (SA) as an approach for solving the problem with uncertainty in travel time between two nodes. According to a review paper on the application of operation research to improve solid waste management system planning, uncertainty affecting the system characteristics such as waste generation rates and transportation costs was poorly addressed in the literature [17]. Capacity planning and optimum selection of system facilities in MSW management system under uncertainties in the waste quantities as well as the capacity of facilities were carried out by Srivastava and Neme [18]. They applied a fuzzy parametric programming approach to address the uncertainties involved the planning of the system over a long time horizon. Lu et al. [19] proposed a model to explore the optimal trade-off between cost-efficiency and mitigation of three types of greenhouse gases including CO_2, CH_4, and N_2O under a set of system uncertainties. The work of Xu et al. [20] is the first research attempt in MSW management system that applied an enhanced fuzzy robust optimization model to handle uncertainty involved in the system planning. This study is an extension version of applying fuzzy robust optimization model in MSW management system [21]. Dealing with the fuzzy constraints based upon multiple algorithms and incorporating fuzzy violation variables into the model are the distinguishing features of their proposed approach. Their model involves different types of fuzzy parameters, including waste quantities produced at each generation node, the economic parameters, as well as operating capacity parameters of system facilities. The main idea of representing capacity parameters as fuzzy numbers in a MSW management system is this fact that the capacity of each facility is affected by different factors such as the operation manner of workers, the quality of the maintenance processes, and service time. The objective function of this model involves economic considerations, including the transportation costs as well as the construction and operation costs associated with system facilities. The applicability of this study was illustrated by a real case study wherein the solid waste management case of the City of Dalian, China.

As the literature on MSW management system shows the performance of such systems in both economical and environmental aspects is significantly influenced by high level of uncertainty involved in its long-term planning. Most of the system parameters such as waste generation rates, transportation and establishment costs, and facilities' capacities in real word situations are uncertain. Although this study is based on the mathematical programming model developed by Jabbarzadeh et al. [12], this study tries to design MSW management system in an uncertain environment. Therefore, the MSW management system under study consists of waste generation nodes, waste transfer stations, and disposal facilities. To handle the uncertainties involved in this study, Robust Possibilistic Programming (RPP) approach is applied. The rest of this paper is structured as follows. Section 2 provides a description of the problem and its formulation. Methodology is presented in Section 3. Section 4 introduces the MSW management system of the case study and the RPP-II model is implemented for it. Numerical results are given in Section 5. Finally, conclusion remarks are presented in Section 6.

Problem description

Consider a MSW management system, in which the waste generated by different municipalities are concentrated on a set of generation nodes. The waste management system is responsible for gathering and processing these wastes by taking account of system economy and environmental considerations simultaneously. The components of this system involve waste generators, transfer stations, and landfills. There are two options for vehicles after collection of wastes: (1) directly ship to the terminal disposal, and (2) ship to the landfills after processing and compacting the collected wastes at transfer stations. Note that applying different types of technologies at each transfer station imposes different costs and energy consumptions to the system. Other assumptions of this study are as follows:

- Number of transfer stations can be stablished are limited.
- Transfer stations are capacitated.
- There exist three kinds of vehicles in fleet of vehicles including collection vehicles, semi-trailers, and trucks.
- Collection vehicles are homogeneous and they are used for shipping waste from generation nodes to transfer stations and landfills.
- Semi-trailers (or trucks) are homogeneous and they are used for shipping compacted waste from transfer stations to landfills.

- It is assumed that the maximum allowable capacity of collection vehicles is less than that of two others.
- There exist several technology levels for compacting waste at transfer stations, in which only one of them can be stablished at a transfer station.
- There exist different landfills.
- It is assumed that using transfer stations in MSW management system can lead to a substantial saving in system costs than the state of directly shipping collected waste to landfills.
- Amounts of waste generated at different generation nodes, transportation costs in different routes, and some factors associated with transfer stations such as capacity limitations, costs are assumed to be fuzzy parameters.

In spite of the fact that most of the system parameters are tainted by high level of uncertainty in real word situations, all of these assumptions were considered in a completely certain environment in the proposed model by Jabbarzadeh et al. [12]. Therefore, in order to increase the ability of the model to deal with real-life situations, this study aims to develop the aforementioned model by considering fuzzy parameters. This study tries to make proper decisions about site selection of transfer stations, the optimal number of these facilities and their adopted technologies, amounts of shipments from each waste generation node to transfer stations and landfills, amounts of shipments between transfer stations and landfills, and the number of transfer vehicles at each generation nodes and transfer station in an uncertain environment. Two criteria including minimization of the total costs and minimization of the greenhouse gas emission are considered in this study to achieve this goal. Unlike the work of Jabbarzadeh et al. [12], energy consumption is considered as a part of the operation cost in cost objective. Furthermore, the developed model in this study considers the amount of cost savings resulting from the establishment of transfer stations for a long time planning horizon in the cost function. Formulation of a fuzzy mathematical programming model for this system is done based on the notations are given in below. The objectives and constraints of this model are as Eqs. (1)-(13).

Sets

G	set of waste generation nodes indexed by s
T	set of transfer station nodes indexed by t
F	set of landfill nodes indexed by f
Q	set of technology levels at transfer stations indexed by q

Parameters

$S\tilde{C}C$	shipment cost for a collection vehicle (per km)
$S\tilde{C}T_q$	shipment cost for a transfer station vehicle with technology level $q \in Q$ (per km)
$E\tilde{C}_{qt}$	establishment cost of transfer station $t \in T$ with technology level $q \in Q$
$C\tilde{S}_{qt}$	cost saving resulting from establishment of transfer station $t \in T$ with technology level $q \in Q$
$V\tilde{C}_{qt}$	variable cost of compacting waste at transfer station $t \in T$ with technology level $q \in Q$
dis_{ij}	distance between node *i* and node *j*; $i, j \in G \cup T \cup F$
$N^{\max}$	maximum number of transfer stations
$\tilde{C}_t$	capacity of transfer station $t \in T$
$C_t^{\min}$	minimum capacity required to establish transfer station $t \in T$
$G\tilde{C}$	amount of greenhouse gas emission from a collection vehicle (per km)
$G\tilde{T}_q$	amount of greenhouse gas emission from a transfer station vehicle with technology level $q \in Q$ (per km)
$G\tilde{W}$	amount of greenhouse gas emission from waste (per cubic meter of waste and per km)
$G\tilde{C}W_q$	amount of greenhouse gas emission from waste compacted with technology level $q \in Q$ (per cubic meter of waste and per km)
β_q	percentage of volume reduction for technology level $q \in Q$
$\tilde{D}_g$	total amount of waste generated at generation node $g \in G$
CC	capacity of a collection vehicle
CT_q	capacity of a transfer station vehicle with technology level $q \in Q$

Decision variables

X_{gtq}	total amount of waste transferred from generation node $g \in G$ to transfer station $t \in T$ with technology level $q \in Q$ (in cubic meter)
Y_{tfq}	Total amount of waste transferred from transfer station $t \in T$ with technology level $q \in Q$ to the landfill $f \in F$ (in cubic meter)
Z_{gf}	Total amount of waste transferred from generation node $g \in G$ to the landfill $f \in F$ (in cubic meter)
A_{qt}	equal to 1 if a transfer station with technology level $q \in Q$ is stablished at node $t \in T$; 0 otherwise
CNT_{gt}	Number of waste collection vehicles for transferring waste from generation node $g \in G$ to transfer station $t \in T$
CNF_{gf}	Number of waste collection vehicles for transferring waste from generation node $g \in G$ to the landfill $f \in F$
TN_{tqf}	Number of vehicles for transferring waste from transfer station $t \in T$ with technology level $q \in Q$ to the landfill $f \in F$

$$
\begin{aligned}
Min\ f_1(x) = {} & \sum_{t \in T}\sum_{q \in Q} \widetilde{EC}_{qt} \times A_{qt} \\
& + \sum_{g \in G}\sum_{t \in T}\sum_{q \in Q} \widetilde{VC}_{qt} \times X_{gtq} \\
& + \sum_{g \in G}\sum_{t \in T} \widetilde{SCC} \times dis_{gt} \times CNT_{gt} \\
& + \sum_{g \in G}\sum_{f \in F} \widetilde{SCC} \times dis_{gf} \times CNF_{gf} \\
& + \sum_{t \in T}\sum_{q \in Q}\sum_{f \in F} \widetilde{SCT}_q \times dis_{tf} \times TN_{tqf} \\
& - \sum_{t \in T}\sum_{q \in Q} \widetilde{CS}_{qt} \times A_{qt}
\end{aligned}
\tag{1}
$$

$$
\begin{aligned}
Min\ f_2(x) = {} & \sum_{g \in G}\sum_{t \in T} \widetilde{GC} \times dis_{gt} \times CNT_{gt} \\
& + \sum_{g \in G}\sum_{f \in F} \widetilde{GC} \times dis_{gf} \times CNT_{gf} \\
& + \sum_{t \in T}\sum_{q \in Q}\sum_{f \in F} \widetilde{GT}_q \times dis_{tf} \times TN_{tqf} \\
& + \sum_{g \in G}\sum_{q \in Q}\sum_{t \in T} \widetilde{GW} \times dis_{gt} \times X_{gtq} \\
& + \sum_{t \in T}\sum_{q \in Q}\sum_{f \in F} \widetilde{GCW}_q \times dis_{tf} \times Y_{tfq} \\
& + \sum_{g \in G}\sum_{f \in F} \widetilde{GW} \times dis_{gf} \times Z_{gf}
\end{aligned}
\tag{2}
$$

$$\sum_{t \in T}\sum_{q \in Q} A_{qt} \le N^{\max} \tag{3}$$

$$\sum_{t \in T}\sum_{q \in Q} X_{gtq} + \sum_{f \in F} Z_{gf} \ge \tilde{D}_g \quad ; \forall g \tag{4}$$

$$(1-\beta_q) \times \sum_{g \in G} X_{gtq} = \sum_{f \in F} Y_{tqf} \quad ; \forall t, q \tag{5}$$

$$\sum_{g \in G} X_{gtq} \le \tilde{C}_t \times A_{qt} \quad ; \forall t, q \tag{6}$$

$$\sum_{g \in G} X_{gtq} \ge C_t^{\min} \times A_{qt} \quad ; \forall t, q \tag{7}$$

$$\sum_{q \in Q} A_{qt} \le 1 \quad ; \forall t \tag{8}$$

$$\sum_{q \in Q} X_{gtq} \le CNT_{gt} \times CC \quad ; \forall g, t \tag{9}$$

$$Z_{gf} \le CNF_{gf} \times CC \quad ; \forall g, f \tag{10}$$

$$Y_{tqf} \le TN_{tqf} \times CT_q \quad ; \forall t, f, q \tag{11}$$

$$X_{gtq}, Y_{tqf}, Z_{gf} \ge 0 \quad ; \forall g, t, f, q \tag{12}$$

$$
\begin{aligned}
& CNT_{gt}, CNF_{gf}, TN_{tqf}, A_{qt} \text{ is integer} \\
& \text{and } A_{qt} \in \{0,1\} \quad ; \forall g, t, f, q
\end{aligned}
\tag{13}
$$

This model formulated as a fuzzy bi-objective mixed integer linear programming model with two objective functions in both economic and environmental aspects. Equation (1) as the cost objective function aims to minimize the sum of the fixed cost of establishing transfer stations, their operating cost, as well as the total waste transportation cost in different routes minus the amount of cost saving is estimated for a long time planning horizon resulting from establishment of transfer stations. Equation (2) represents the second objective function calculated the amount of greenhouse gas emission. The first three terms in Equation (2) are associated to the amount of greenhouse gas emitted by vehicle fleet in planned waste transfer routes, whereas the second three ones correspond to the amount of greenhouse gas sent out by compacted and uncompacted waste during their shipment. Equation (3) guarantees that the total number of transfer stations will be stablished does not exceed the certain maximum number of transfer station. Equations (4) represent the flow conservation constraints during the collection of waste. According to this set of constraints, total amount of waste generated at different generation nodes is shipped to transfer stations or landfills. The flow balance constraint for each transfer station is formulated through Equations (5). Equations (6)- (7) correspond to the capacity constraints of the transfer stations. In other words, the total amount of waste processed at each transfer station should not exceed its capacity. Furthermore, a transfer station is not established if its minimum capacity requirement is not satisfied. Equations (8) ensure that at most one technology level can be stablished at each potential transfer station. In different routes, the total amounts of uncompacted waste transferred by collection vehicles do not exceed their capacities, these constraints are formulated through Equations (9)- (10). Analogous constraints for other types of vehicles are given at Equations (11). Non-negative and integer decision variables are defined by Equations (12) and (13) respectively.

Methodology

Robust Possibilistic Programming

Provision of Decision Maker (DM)'s risk aversion as well as favorable service-level function in optimization problems tainted by great level of uncertainty is became possible through robust optimization. In other words, the main feature of solutions obtained using robust optimization approaches is less sensitivity to changes in problem's input data.

Possibilistic programming is a special class of fuzzy mathematical programming approach. This approach is able to handle the imprecise coefficients of objective functions and constraints of optimization problems. With respect to the characteristics of the problem under consideration in this study that mentioned in previous section, it is possible to benefit from advantages of robust optimization and possibilistic programming simultaneously. Pishvaee et al. [22] proposed different versions of Robust Possibilistic Programming (RPP) approaches and compared their weaknesses and strengths for an industrial case study. The results of their study as well as some relevant studies (e.g., [23]) were shown that RPP-II has a better performance than other versions of RPP solution approaches. Therefore, this study applies this version of RPP approaches for the proposed model.

To facilitate the implementation of RPP-II approach in this study, consider the compact form of the developed bi-objective mathematical programming model as follows:

$$
\begin{aligned}
& Min\ f_1 = \tilde{C}x + \tilde{F}y + \tilde{G}z \\
& Min\ f_2 = Hx + Vz \\
& s.t. \quad Bx = 0, \\
& \qquad Lx \geq \tilde{D}, \\
& \qquad Rx \leq \tilde{S}y, \\
& \qquad Rx \geq Ty, \\
& \qquad Wx \leq Qz, \\
& \qquad Ay \leq 1, \\
& \qquad x \geq 0,\ y \in \{0,1\},\ z \in \{Z - \bar{Z}\}.
\end{aligned} \tag{14}
$$

Where fuzzy vectors $\tilde{C}$, $\tilde{F}$, $\tilde{G}$, $\tilde{D}$, and $\tilde{S}$ are associated to variable operation costs, fixed cost and long-term cost savings corresponded to the transfer stations, variable transportation cost, amount of solid waste generated at different districts, and capacity limitation of system facilities, respectively. H and V are crisp vectors of technological coefficients and shows the amount of greenhouse gas emission from waste and vehicle fleet. Also, A, B, L, R, T, W and Q are the coefficient matrixes of the problem's constraints. Three types of decision variable including non-negative continuous variables, binary variables, and non-negative integer variables are introduced by vectors x, y, and z respectively.

Note that the formulation of the imprecise parameters is done based on trapezoidal fuzzy numbers. By applying the expected value operator and necessity measure used to cope with possibilistic objective functions and chance constraints respectively, the linear form of RPP-II model for the problem under consideration in this study is formulated as Equations (15). For detail information about RPP-II as well as different versions of RPP approaches and their formulations, refer to Pishvaee et al. [22].

$$
\begin{aligned}
& Min\ \mathrm{W}_1 = E[f_1] + \gamma\left(f_{1\max} - E[f_1]\right) \\
& \qquad + \delta\left(D_{(4)} - (1-\alpha)D_{(3)} - \alpha D_{(4)}\right) \\
& \qquad + \pi\left(S_{(1)}v + (y - v)S_{(2)} - S_{(1)}y\right) \\
& Min\ \mathrm{W}_2 = E[f_2] + \delta\left(D_{(4)} - (1-\alpha)D_{(3)} - \alpha D_{(4)}\right) \\
& \qquad + \pi\left(S_{(1)}v + (y - v)S_{(2)} - S_{(1)}y\right) \\
& s.t. \quad Bx = 0, \\
& \qquad Lx \geq (1-\alpha)D_{(3)} + \alpha D_{(4)}, \\
& \qquad Rx \leq \left((y - x)S_{(2)} + S_{(1)}v\right)y, \\
& \qquad v \leq My, \\
& \qquad v \geq M(1-y) + \beta, \\
& \qquad v \leq \beta, \\
& \qquad Rx \geq Ty, \\
& \qquad Wx \leq Qz, \\
& \qquad Ay \leq 1, \\
& \qquad x,\ v \geq 0,\ y \in \{0,1\},\ z \in \{Z - \bar{Z}\}, \\
& \qquad 0.6 \leq \alpha,\ \beta \leq 1
\end{aligned} \tag{15}
$$

The first term in both objective functions of Equations (15) corresponds to the expected value of the objective function. The concept of optimality robustness is formulated through the second term of the first objective function in which the objective function is only sensitive to the over-deviation of the objective function value from its expected value. Two second terms of the first objective functions refer to the feasibility robustness that ensure the objective function is only sensitive to under-deviation of amount of waste as well as over-deviation of capacity limitation, respectively. You can see the terms associated with optimality and feasibility robustness in the second objective function once again.

ε-Constraint method

The developed model in this study includes two conflict objective functions. To handle problems with more than one objective function, various methods have been proposed. ε-Constraint is a well-known method applied for this purpose introduced by [24]. Providing an acceptable approximation of Pareto front in such problems is the prominent feature of this method. This technique enables decision makers to transform a multi-objective optimization problem into a series of single-objective problems can be optimally solved by commercial optimization solvers. ε-Constraint involves optimization of main objective function subject to a set of primary constraints of problem as well as the unequal constraints associated to other objective functions. Therefore, it is necessary to calculate the optimal and nadir values of each objective function by solving the respective single-objective model separately. By considering the importance of cost objective in comparison with environmental issues, in this study the first objective is preserved as the primary objective function and the ε-constraint model is formulated as follow:

$$
\begin{aligned}
& Min\ W_1 \\
& s.t.\ \ W_2 \leq \varepsilon, \\
& \qquad x \in F(x).
\end{aligned} \tag{16}
$$

Where $F(x)$ states the primary constraints of the problem. By systematically variation of the right-hand side value of the first constraint (i.e., ε) in the range of second objective function, it is possible to achieve different Pareto solutions. Full details about ε-Constraint method is achievable in the work of [25].

Experiment

This section tries to apply the proposed model for a real case associated with the MSW management system of Tehran, the capital of Iran.

An ordinary method for Tehran's MSW management is landfilling. Aradkooh Center, Ab'ali Center, and Khavaran Center are three active landfilling sites. It is should be noted that Khavaran Center is assigned to landfilling the construction and demolition wastes, and the most of Tehran's solid waste landfills in two other centers that located in the south and east of the city. Also, the MSW management system involves eleven active transfer stations. Currently, these stations are only responsible for collecting and transferring the wastes to the landfills. In other words, no processing operations take place in these sites.

With respect to the increasing trend in waste generation in urban regions, the current infrastructures of the MSW system is not sufficiently proper and it is essential to improve the system by applying more efficient facilities. In this regard, the managers of Tehran Waste Management Organization have found that the application of waste compacting technologies in transfer stations can enhance the system productivity. Therefore, in addition to existing transfer stations, five locations have been selected as potential sites for constructing new ones with compacting technologies. Information about the amount of waste can be transferred to these potential facilities from different regions are provided in Table 1 in the form of triangular fuzzy numbers. Table 2 presents the distance between potential locations of transfer stations and the 22 urban regions of Tehran city as well as the two landfills Aradkooh Center and Ab’ali Center [12]. Based on experts’ views, among different compacting technologies can be adopted at the system facilities, the implementation of two alternatives are evaluated in this study. The characteristics of these technologies are compared in Table 3. The required capital for establishing each transfer station by considering different technology levels and their capacities are given in Table 4. Unfortunately, it is not possible to achieve the exact amount of the other parameters of the problem such as the parameters related to amount of gas emission and some cost parameters. Therefore, the other required data are estimated.

Table 1 - The amount of waste generated at each region

R.	Amount of waste	R.	Amount of waste
1	(58, 65, 74, 85)	12	(205, 218, 215, 226)
2	(218, 232, 244, 255)	13	(127, 134, 147, 155)
3	(78, 90, 100, 106)	14	(175, 188, 196, 206)
4	(130, 140, 154, 160)	15	(264, 275, 286, 295)
5	(78, 85, 93, 100)	16	(95, 102, 115, 123)
6	(119, 125, 133, 140)	17	(226, 238, 246, 253)
7	(147, 152, 164, 175)	18	(207, 218, 232, 245)
8	(250, 262, 278, 285)	19	(195, 210, 221, 228)
9	(155, 168, 179, 188)	20	(114, 122, 135, 144)
10	(215, 222, 236, 245)	21	(173, 180, 196, 202)
11	(150, 160, 172, 179)	22	(68, 76, 85, 92)

Table 2 - Comparison of two compacting technology levels

Characteristic	Technology level 1	Technology level 2
Establishment cost	Less expensive	Most expensive
Compaction rate	Up to 35%	Up to 45%
Energy consumption	High	Low
Vehicle fleet	Semi-trailer	Truck

Table 3 - Length of all possible routes

To / From	Potential transfer station					Landfill	
	1	2	3	4	5	1	2
R1	5.1	21.6	17.1	19.1	30.5	19.1	30.5
R2	16.3	13	25.7	25.6	21.9	25.6	21.9
R3	15.6	12.1	16.9	22.3	20.7	22.3	20.7
R4	11.4	15.8	24.4	12.9	30	12.9	30
R5	26	17.2	12.6	44.9	39	44.9	39
R6	18	6.1	19.6	7.1	21.6	7.1	21.6
R7	14.9	19.6	28.2	10.2	27.3	10.2	27.3
R8	16.5	23.2	31.8	14.5	29.9	14.5	29.9
R9	25.4	1.1	13.3	16.6	19.6	16.6	19.6
R10	28.8	4.6	18.2	9	16	9	16
R11	18	10	23.7	5.1	25.7	5.1	25.7
R12	16.5	12.2	30.6	5.5	24.2	5.5	24.2
R13	17.1	10.3	31.5	4.6	23.2	4.6	23.2
R14	22.8	17.2	35.4	0	18.7	0	18.7
R15	29.1	13.1	31.4	6.5	14.7	6.5	14.7
R16	29.6	5.1	18.7	8.8	15.6	8.8	15.6
R17	31.3	7	16	20.8	14.7	20.8	14.7
R18	31.2	11.6	25	10.3	12.4	10.3	12.4
R19	32.4	26.9	37.9	14.1	14.5	14.1	14.5
R20	29.2	4.9	13.1	25.6	19.2	25.6	19.2
R21	11.4	15.8	24.4	12.9	30	12.9	30
R22	28.3	16.1	6.1	39.7	38.8	39.7	38.8
Landfill 1	70	45	50	25	22	-	-
Landfill 2	25.4	39.9	48.4	31.3	44.5	-	-

Table 4 - Capacity and establishment cost of different technology levels at each transfer station

T.S.	Establishment cost of each technology level (E+6)	Capacity
1	L1: (105, 112, 120, 135) L 2: (545, 583, 605, 617)	(1520, 1574, 1620, 1650)
2	L 1: (137, 142, 149, 155) L 2: (640, 675, 690, 720)	(1900, 1945, 1985, 2020)
3	L 1: (137, 142, 149, 155) L2: (720, 735, 770, 830)	(2200, 2248, 2285, 2300)
4	L 1: (105, 112, 120, 135) L2: (545, 583, 605, 617)	(1600, 1650, 1695, 1720)
5	L1: (52, 57, 60, 64) L 2: (275, 290, 310, 328)	(820, 846, 883, 905)

Numerical results

This section is assigned to solve the developed RPP-II model based on ε -constraint method for a data set associated to the MSW management system of Tehran. It is should be noted that the model is implemented in GAMS software, version 24.1.3 and solved with CPLEX solver. An Intel Corei7 PC with 8 GB of RAM and over 2 GHz CPU is used for this purpose. As mentioned before, since RPP-II approach enables DM to determine the favorable satisfaction level of chance constraints, different values of minimum confidence level of chance constraints (i.e., α and β) including 0.6, 0.7, 0.8, and 0.9 are used to analyze the performance of the model. In order to achieve an approximation of Pareto front as well as to make sense about conflicting nature of objective functions, ten points in the range of the second objective function divided it to equal parts are selected. The Pareto optimal solutions under different minimum confidence levels are reported in Table 5. The obtained results indicate that when DM select a higher value for minimum confidence level, the values of both objective functions increase. The results under minimum confidence level 0.7 are summarized in Figure 1. As it can find from Figure 1, the bi-objective mathematical programming under study includes two conflict objective functions as improving in the value of one objective leads to degrading at the other objective. Figure 2 demonstrate the details of Pareto solutions 4. The transfer station should be established as well as the all planed routes in the MSW network are shown in this figure.

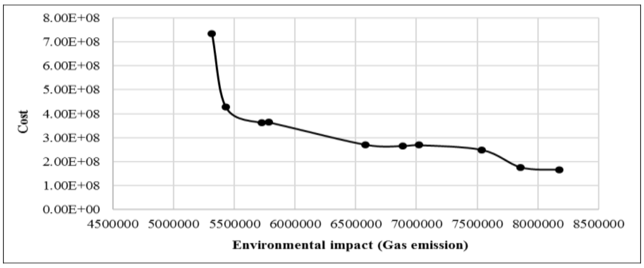

Figure 1 - The Pareto optimal solution under minimum confidence level 0.7

Table 5 - Pareto solutions under different minimum confidence levels

$\alpha^{\min}$ $\beta^{\min}$	Objective function value		CPU time	Number of open facilities
	W_1	W_2		
0.6	1.641281E+8	8180779	3.437	3
	1.752819E+8	7859234		3
	2.304997E+8	7537689		3
	2.609843E+8	6882500		2
	2.667223E+8	6573053		2
	2.678272E+8	6542705		2
	3.586709E+8	5705340		1
	3.594063E+8	5714812		1
	4.287577E+8	5467002		0
	7.291641E+8	5286872		1
0.7	1.654069E+8	8177630	4.697	3
	1.756182E+8	7859957		3
	2.482579E+8	7542048		3
	2.682566E+8	7024197		2
	2.652204E+8	6889832		2
	2.699034E+8	6584012		2
	3.631547E+8	5788373		1
	3.610127E+8	5729346		1
	4.264558E+8	5431267		0
	7.335520E+8	5316688		1
0.8	1.710016E+8	8214698	5.030	3
	1.684790E+8	7951455		3
	1.723923E+8	7688212		3
	2.632942E+8	6929515		2
	2.686962E+8	7030119		2
	2.690647E+8	6898482		2
	2.706645E+8	6596650		2
	3.622995E+8	5735620		1
	3.630348E+8	5745144		1
	4.606078E+8	5845510		0
0.9	1.694510E+8	8219198	3.595	3
	1.752659E+8	7908027		3
	2.210422E+8	7596857		3
	2.638217E+8	6936445		2
	2.697100E+8	6974515		2
	2.706645E+8	6596650		2
	3.631148E+8	3767204		1
	3.623795E+8	5757645		1
	4.253209E+8	5453065		0
	7.367570E+8	5418661		1

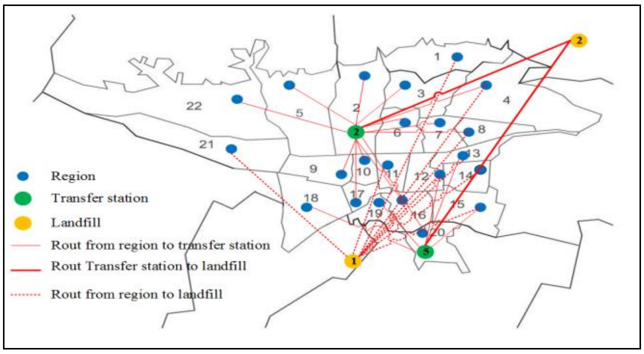

Figure 2 - The Pareto solution 4 under minimum confidence level 0.7

To evaluate the performance of the RPP-II approach in terms of desirability and robustness of the derived solutions, different realizations of the problem under study are needed. For this purpose, the imprecise parameters of the problem are randomly generated based on uniform distributions in the range of respective trapezoidal fuzzy numbers.

Conclusion

In this study, a bi-objective fuzzy mathematical programming model is proposed for the design of solid waste management system by considering two conflicting objective functions including minimization of total costs as well as minimization of the greenhouse gas emissions. A version of Robust Possibilistic Programming (RPP) approach i.e. RPP-II is used to cope with uncertain parameters of the problem. ε-constraint method is utilized to solve the bi-objective model and achieve an acceptable approximation of Pareto optimal solutions. Applicability of the proposed model in practice is illustrated through the Tehran MSW system where results show that the optimal solution requires adopting less expensive compacting technologies. Incorporation of vehicle routing decisions into the model and employing other types of RPP models, including the hard worst-case, the soft worst-case and the realistic RPP approaches can be considered as recommendations for future researches.

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