Journal of Quality Engineering and Production Optimization

Vol. 5, No. 1, Winter & Spring 2020

http://jqepo.shahed.ac.ir

Research Paper

DOI: 10.22070/JQEPO.2020.5733.1166

A Fuzzy Location-Allocation Problem for Sustainable Design of a Municipal Solid Waste Management Network

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***Abstract** – The municipal concrete waste production has grown recently due to the urban population's considerable increment. With the advances in technology, SWM (solid waste management) has been a significant challenge for many countries worldwide. Therefore, in this paper, a multi-objective mixed-integer linear programming model with three objectives, maximizing job opportunities and minimizing costs and carbon emissions, is extended under uncertainty. A fuzzy goal programming approach is applied to deal with uncertain parameters and solve the proposed multi-objective model. A case study is employed for waste management in Tehran's fifteen urban areas to demonstrate the proposed model's efficiency. Ultimately, the model is solved using the CPLEX solver of GAMS software, and a sensitivity analysis is performed to assess the results.*

***Keywords**– Fuzzy goal programming, Location-allocation problem, Multi-mode transportation, Municipal solid waste management, Sustainable waste management.*

I. INTRODUCTION

The problem of waste management, as one of the most critical issues, affects, and concerns humanity. 1.3 ×109 t of municipal solid waste (MSW) are produced worldwide per annum or 1.2 kg/capita/d. It is prognosticated to go up to 2.2×109 t/y by 2025 or 1.42 kg/person/d (Hoornweg & Bhada-Tata, 2012).

The collection and disposal of municipal solid waste have become crucial by the escalation of its production. World Bank (2012) stated that they had gathered less than 50% of the produced municipal solid waste in countries with lower revenues, such as Ghana, Ethiopia, etc. Considerable pressure has been exerted by Solid Waste Management (SWM) on the local authorities. Approximately 20 to 50 percent of the municipalities' budget in developing countries is currently allocated for Solid Waste Management (Sharholy et al., 2008; Lohri et al., 2014; Herva et al., 2014).

Municipal Solid Waste is regarded as the most complex solid waste streams caused by two parts of society: the household/residential and the business/commercial. A growing consciousness of the long-term and short-term effects of SWM services results in the responsible authorities giving considerable attention to these particular sustainability dimensions.

Manuscript Received:15-Jan-2020 & Revised: 18-March-2020 & Accepted: 26-May-2020
ISSN: 2423-3781

Hence, it cannot be considered entirely satisfactory to plan a municipal solid waste management system only according to economic assumptions (Thikimoanh et al., 2015; Rabbani et al., 2019).

In the eighties and nineties, sustainable development started to be addressed, and the conclusion was drawn that economic, environmental, and social dimensions are required to be investigated; if not, limited resources on the Earth might not satisfy the requirements of the future generations (Edalatpour et al., 2018).

It is possible to classify waste from different viewpoints: the physical state (solid, liquid, and gas), the main applications (packaging, food industries, etc.), the materials (glass, paper, etc.), the physical features (need to be burned, have the potential of sundry reuse or recovery), the origin (household, commercial, agricultural, industrial, etc.), and its safety (safe or dangerous) (Edalatpour et al., 2018).

A municipal solid waste management system comprises different economic, social, and environmental implications, like waste production, transportation, treatment, and disposal (Wilson, 1985). In preceding studies, several models and evaluation approaches were applied to support MSW management (Beigl et al., 2008; Khan & Faisal, 2008; Su et al., 2008).

Paul et al. (2018) introduced a mathematical model for the waste management system optimization, and from then on, numerous studies have extended solid waste management models as decision-support approaches for choosing technology, locating, and sizing waste processing facilities.

Ghiani et al. (2014) developed an integrated waste gathering system and decided on the gathering time and number of staff needed in this system. Ghiani et al. (2015) proposed a model to site centers of waste collection and make decisions on the sort of collection bins.

To deal with the obnoxious waste location-routing problem, Asgari et al. (2017) presented a model with multiple objectives using an efficient algorithm and taking into account different kinds of wastes and several treatment technologies.

Hrabec et al. (2018) proposed a model for deciding in MSW management by combining waste generation and treatment process according to greenhouse gas evaluation to decrease the generated waste. To determine the optimal routes, Louati (2016) introduced an MSW collection model to maximize the quantity of collected waste and minimize the environmental emission concerning vehicles.

LV et al. (2020) extended an optimization model utilizing the p-median technique to optimize locating the recycling sites and prognosticated the municipal concrete waste production. Ng et al. (2013) appraised the possibility of substitution of energy stemmed from MSW for the fossil fuels consumed in small cities taking into account diverse factors.

To appraise MSW management strategies, ThiKimOanh et al. (2015) extended a model to determine the optimal distribution of MSW from population area to treatment centers. Yousefloo & Babazadeh (2020) proposed a bi-level mathematical model with multiple objectives to optimize the MSW management network utilizing the Stackelberg game approach and considering a case study to demonstrate the model's capability. To develop a decision support system for sustainable municipal solid waste management, Hoang et al. (2019) presented a multi-objective optimization model considering a non-linear programming approach. Heidari et al. (2019) presented a multi-objective mathematical programming model that considers new employment opportunities as the social side of sustainability in an uncertain environment. Besides, the literature gap is denoted in Table I.

TABLE I. COMPARISON OF THE INTRODUCED MODEL WITH PREVIOUS STUDIES

Articles	***Objective function***		***Sustainability***	***Model assumptions***				***Case study***	***Solution approach***	
	Single	Multi		Multi-mode	Types of SW	Multi-period	Facility technology		Deterministic	Uncertainty
Ng et al. (2013)	profit						✓	✓	MILP and CPLEX solver	
Zhang et al. (2014)	Cost					✓				Linear Chance constrained programming
Thikimonah et al. (2015)	Cost		✓				✓	✓	Scenario based decision- making	
Louati (2016)		*Cost *Environmental emission	✓	✓				✓	MILP and AHP method	
Asgari et al. (2017)		*Cost *Undesirability *Risk			✓		✓	✓	memetic algorithm	
Pramanik et al. (2018)		*Cost *GHG emission *Revenue	✓							Fuzzy programming
Hrabec et al. (2018)		*Cost *GHG emission							Scenario based decision-making	
Paul et al. (2018)	Cost			✓				✓	Linear programming solved by LINGO	
LV et al. (2020)	Cost			✓				✓	p-median optimization model	
Yousefloo & Babazadeh (2020)		*Cost *GHG emission	✓	✓	✓		✓	✓	MOMILP model solved by the augmented ε-constrained method	
Current study		*Cost *CO2 emission *Job opportunities	✓	✓	✓	✓	✓	✓		MOMILP model solved by fuzzy goal programming

Note: GHG denotes Greenhouse gas; MOMILP represents Multi-objective mixed-integer linear programming; SW shows solid waste.

As represented in Table I and according to the existing literature, the most critical gaps in the literature covered in this paper are as follows. In Asgari et al. (2017) and Yousefloo & Babazadeh (2020), various solid waste types have been considered. Moreover, sustainability in solid waste management has been taken into account in Louati (2016), Pramanik et al. (2018), and Yousefloo & Babazadeh (2020). Furthermore, Zhang et al. (2014) have assumed the multi-period assumption in a mathematical model to design a solid waste management system. Even though job opportunity is one of the most critical issues in sustainability, only a few studies have considered it.

Concerning the literature gaps mentioned above, in this paper, a new multi-objective mixed-integer linear programming (MOMILP) model with three objective functions, namely maximizing job opportunity as well as minimizing cost and CO_2 emission, is presented under uncertainty. Therefore, the main novelties of this paper are as follows. A fuzzy goal programming approach is applied in this paper for municipal solid waste management problem in order to deal with the proposed multi-objective model under uncertainty. Furthermore, different facility technologies, permanent and temporary facilities, diverse types of solid wastes, multi-mode transportation, and multi-period assumption are considered simultaneously in an integrated MOMILP model for sustainable design of municipal solid waste management network.

The rest of this article is organized as follows. The introduced model is described in Section II. Section III presents the solution approach. In Section IV, the model's applicability is represented employing a case study, and the results are analyzed in Section V. Finally, Section VI provides the concluding remarks.

II. PROBLEM DEFINITION

Houses and organizations produce a large quantity of solid waste per annum. A large amount of wastes is comprised of papers and glasses. Solid wastes are gathered from the areas influenced by them and carried to a solid waste management site, where these wastes will be separated (Habib & Sarkar, 2017). The separated wastes such as glass are conveyed to recycling centers, wastes such as paper are conveyed to incineration centers to generate energy, and the other ones that are mainly organic are sent to landfill. Finally, the ash produced by incinerating wastes is sent to landfill as well. One of the features that make the present investigation distinctive from past studies is considering multi-period planning, temporary and permanent facilities, multi-mode transportation, and facility technology simultaneously. *Fig.* 1 illustrates the schematic diagram of the presented SWM supply chain model. Three conflicting objectives, namely maximizing job opportunity provided while processing waste and minimizing costs and CO_2 emitted while processing waste, are taken into account in the proposed mathematical model.

Furthermore, the facilities' number and locations in addition to the amount of waste transferred among the facilities are determined, and the distribution channel from the solid waste storage centers to the facilities is adopted in this SWM supply chain model. Since the problem is uncertain and hard to acquire accurate information, considering deterministic values for the respective parameters might not produce proper outcomes (Shin et al., 2016; Moon et al., 2014). The fuzzy possibility programming method is an appropriate tool for modeling the lack of knowledge regarding uncertain parameters. Possibilistic programming employs possibility distributions in order to manage the uncertainty concerning the parameters. Concerning the nature of a post-disaster situation, input parameters are assumed uncertain in the presented mathematical model, and a triangular possibility distribution is taken into account for uncertain parameters. Thus, the goal programming method is applied to solve the multi-objective model.

A. Model assumptions

The formulation of the introduced model is according to the following assumptions:

- Recyclable wastes are already gathered from MSW in the stage of waste separation. The introduced model is presented given the waste management hierarchy, which needs to gather recyclable waste before further waste processing.
- Collected wastes are transported to separation centers by vehicles with different capacities.
- Solid wastes were gathered from the areas influenced by them and carried to the solid waste management site.
- The amount of MSWs at each solid waste management site is known that are selected from Habib & Sarkar (2017).
- The municipal solid waste considered in this study includes paper and glass, which are the most important solid waste and have the highest production rate.
- There is a limitation on the number of permanent and temporary facilities in each area. Moreover, each kind of facility has a particular capacity constraint.
- Processing facilities are permanent and temporary and can be established on the suburb of the urban network graph. Traditional and modern technology is taken into account for these facilities with various capacities and establishment expenses. These facilities ought to be established at the start of the planning horizon, if necessary.

There exist sufficient financial resources in order to accomplish all essential activities of the solid waste processing operation. There is a need for millions of dollars for solid waste processing operations like collection, transportation, recycling, and incineration facility installation. Sufficient availability of donations or government funds is guaranteed by considering this assumption to carry out all the response waste management operations well.

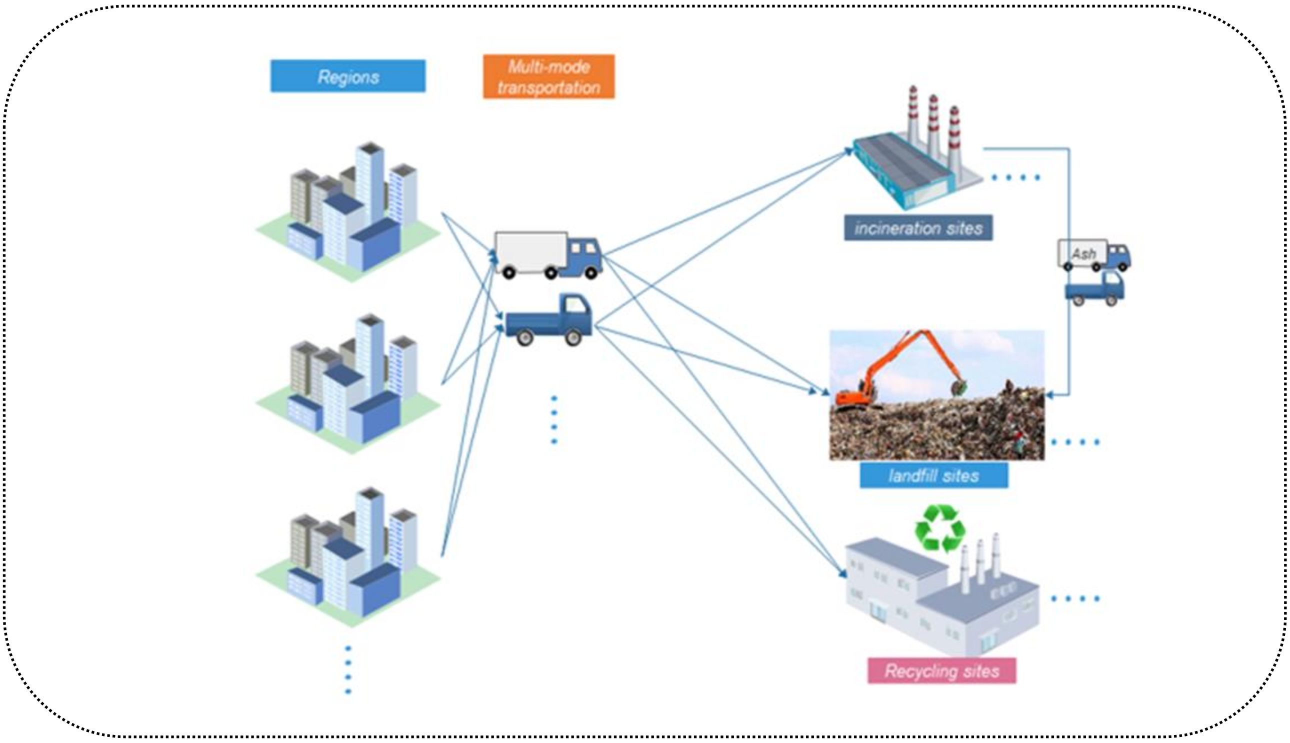

Fig. 1. The schematic diagram of the presented SWM supply chain model

Sets:

i	The set of solid waste management sites $\{i = 1,2,3,...I\}$
j	The set of possible locations for incineration centers $\{j = 1,2,3,...J\}$
k	The set of possible locations for landfill centers $\{k=1,2,3,...K\}$
l	The set of possible locations for recycling centers $\{l=1,2,3,...L\}$
p	The set of waste sorts
f	The set of waste collection facilities ($f=1$ represents permanent facility and $f = 2$ represents temporary facility)
r	The set of waste processing facilities ($r=1$ denotes facility with traditional technology and $r=2$ denotes facility with modern technology)
t	The index of periods
m	The index of transportation modes

Parameters:

α	The upper bound of permanent incineration facilities *j*
α'	The upper bound of temporary incineration facilities *j*
β	The upper bound of permanent recycling facilities *l*
β'	The upper bound of temporary recycling facilities l
γ	The upper bound of permanent landfill facilities k
γ'	The upper bound of temporary landfill facilities k
a_{fjr}	The establishment cost of waste collection facility f at incineration center j with waste processing facility technology r
b_{flr}	The establishment cost of waste collection facility f at recycling center l with waste processing facility technology r
c_{fkr}	The establishment cost of waste collection facility f at landfill center k with waste processing facility technology r
$\tilde{\lambda}_{jpr}$	The total capacity of solid waste type p at incineration center j with waste processing facility technology r
$\tilde{\lambda}_{lpr}$	The total capacity of solid waste type p at recycling center l with waste processing facility technology r
$\tilde{\lambda}_{kpr}$	The total capacity of waste collection facility f at landfill center k with waste processing facility technology r
$\widetilde{pe}_{ipt}$	The total quantity of solid waste type p allocated from wastes influenced areas to solid waste management site i in time t
$\widetilde{va}_{jpt}$	The percent of total solid waste type p at incineration center j transformed into ash in time t
δi_{jp}	The number of job opportunities per ton of solid waste type p processed at incineration center j
δr_{lp}	The number of job opportunities per ton of solid waste type p processed at recycling center l

δl_{kp} The number of job opportunities per ton of solid waste type p processed at landfill center k

$\delta i'_{fjr}$ The number of job opportunities per ton of waste collection facility f with waste processing facility technology r processed at incineration center j

$\delta r'_{flr}$ The number of job opportunities per ton of waste collection facility f with waste processing facility technology r processed at recycling center l

$\delta l'_{fkr}$ The number of job opportunities per ton of waste collection facility f with waste processing facility technology r processed at landfill center k

tre_{ilmp} The transportation cost of solid waste type p from solid waste management site i to recycling center l at transportation mode m

tlf_{ikmp} The transportation cost of solid waste type p from solid waste management site i to landfill center k at transportation mode m

cer_{ilmp} The CO2 emissions of solid waste type p during transportation from solid waste management site i to recycling center l at transportation mode m

cel_{ikmp} The CO2 emissions of solid waste type p during transportation from solid waste management site i to landfill k at transportation mode m

cec_{ip} The CO2 emissions during the collection of solid waste type p at solid waste management site i

$cepi_{fjr}$ The CO2 emissions during the establishment of collection facility f at incineration center j with waste processing facility technology r

$cepr_{flr}$ The CO2 emissions of the number of job opportunities per ton of collection facility f with waste processing facility technology r processed at recycling center l

$cepl_{fkr}$ The CO2 emissions during incineration process of waste collection facility f at landfill k with waste processing facility technology r

cei_{ijmp} The CO2 emissions during transportation of solid waste type p from solid waste management site i to incineration center j at transportation mode m

cel_{jkmp} The CO2 emissions during transportation of solid waste type p from incineration center j to landfill k at transportation mode m

θ_{ip} The Collection cost of solid waste type p at solid waste management site i

ε_{jp} The incineration cost of solid waste type p at incineration center j

μ_{lp} The recycling cost of solid waste type p at recycling center l

σ_{kp} The ash cost of solid waste type p at landfill center k

τ_{ijmp} The transportation cost of solid waste type p from solid waste management site i to incineration center j at transportation mode m

tre_{ilmp} The transportation cost of solid waste type p from solid waste management site i to recycling center l at transportation mode m

tlf_{ikmp} The transportation cost of solid waste type p from solid waste management site i to landfill center k at transportation mode m

tas_{jkmp} The transportation cost of ash of solid waste type p from incineration center j to landfill center k at transportation mode m

cec_{ip} CO2 emissions during the collection of solid waste type p at solid waste management site i

Decision variables:

Positive variables:

π_{ijmpt} The amount of solid waste type p conveyed from solid waste management site i to incineration center j at transportation mode m in time t

πr_{ilmpt} The amount of solid waste type p conveyed from solid waste management site i to recycling center l at transportation mode m in time t

πl_{ikmpt} The amount of solid waste type p conveyed from solid waste management site i to landfill center k at transportation mode m in time t

πa_{jkmpt} The amount of ash of solid waste type p conveyed from incineration center j to landfill center k at transportation mode m in time t

vi_{ipt} The percent of total solid waste type p at solid waste management site i need to be incinerated in time t

vr_{ipt} The percent of total solid waste type p at solid waste management site i need to be recycled in time t

vl_{ipt}	The percent of total solid waste type p at solid waste management site i need to be landfilled in time t

Binary variables:

x_{frjt}	If waste collection facility f via technology r is installed at incineration center j in time t then 1, otherwise 0
y_{frlt}	If waste collection facility f via technology r is installed at recycling center l in time t then 1, otherwise 0
z_{frkt}	If waste collection facility f via technology r is installed at landfill center k in time t then 1, otherwise 0

The Mathematical model

$$Min\ Z1 = \sum_t \sum_f \sum_r \sum_j a_{fjr} x_{frjt} + \sum_t \sum_f \sum_r \sum_l b_{flr} y_{frlt} \tag{1}$$

$$+ \sum_t \sum_f \sum_r \sum_k c_{fkr}\, z_{frkt} + \sum_t \sum_i \sum_p \theta_{ip} pe_{ipt}$$

$$+ \sum_t \sum_m \sum_p \sum_i \sum_j (\varepsilon_{jp} + \tau_{ijmp}) \pi_{ijmpt}$$

$$+ \sum_t \sum_m \sum_p \sum_i \sum_l (\mu_{lp} + tre_{ilmp}) \pi r_{ilmpt}$$

$$+ \sum_t \sum_m \sum_p \sum_i \sum_k (\sigma_{kp} + tlf_{ikmp}) \pi l_{ikmpt}$$

$$+ \sum_t \sum_m \sum_p \sum_j \sum_k (\sigma_{kp} + tas_{jkmp}) \pi a_{jkmpt}$$

$$Min\ Z2 = \tag{2}$$

$$\sum_t \sum_i \sum_p cec_{ip} pe_{ipt} + \sum_t \sum_m \sum_p \sum_i \sum_j cei_{ijmp}\, \pi_{ijmpt}$$

$$+ \sum_t \sum_f \sum_r \sum_j cepi_{fjr} x_{frjt} + \sum_t \sum_m \sum_p \sum_i \sum_l cer_{ilmp}\, \pi r_{ilmpt}$$

$$+ \sum_t \sum_f \sum_r \sum_l cep_{flr} y_{frlt} + \sum_t \sum_m \sum_p \sum_i \sum_k cel_{ikmp}\, \pi l_{ikmpt}$$

$$+ \sum_t \sum_f \sum_r \sum_k cepl_{fkr} z_{frkt} + \sum_t \sum_m \sum_p \sum_j \sum_k cea_{jkmpt}\, \pi a_{ikmpt}$$

$$Max\ Z3 = \tag{3}$$

$$\sum_t \sum_f \sum_r \sum_j \delta i'_{fjr} x_{frjt} + \sum_t \sum_m \sum_p \sum_i \sum_j \delta i_{jp}\, \pi_{ijmpt}$$

$$+ \sum_t \sum_f \sum_r \sum_l \delta r'_{flr} y_{frlt} + \sum_t \sum_m \sum_p \sum_i \sum_l \delta r_{lp}\, \pi r_{ilmpt}$$

$$+ \sum_t \sum_f \sum_r \sum_k \delta l'_{fkr} z_{frkt} + \sum_t \sum_m \sum_p \sum_i \sum_k \delta l_{kp}\, \pi l_{ikmpt}$$

$$+ \sum_t \sum_m \sum_p \sum_j \sum_k \delta l_{kp}\, \pi a_{jkmpt}$$

S.t.

$$\sum_i \sum_m \pi_{ijmpt} \le \tilde{\lambda}_{jpr} x_{frjt} \tag{4}$$

$$\sum_i \sum_m \pi r_{ilmpt} \le \tilde{\lambda}_{lpr} y_{frlt} \tag{5}$$

$$\sum_i \sum_m \pi l_{ikmpt} + \sum_j \sum_m \pi a_{jkmpt} \le \tilde{\lambda}_{kpr} z_{frkt} \tag{6}$$

$$\widetilde{pe}_{ipt} - \sum_j \sum_m \pi_{ijmpt} - \sum_l \sum_m \pi r_{ilmpt} - \sum_k \sum_m \pi_{ikmpt} = 0 \tag{7}$$

$$\sum_k \sum_m \pi a_{jkmpt} = \sum_i \sum_m \widetilde{va}_{jpt} \pi_{ijmpt} \tag{8}$$

$$\sum_l \sum_m \pi r_{ilmpt} = vr_{ipt} \widetilde{pe}_{ipt} \tag{9}$$

$$\sum_j \sum_m \pi_{ijmpt} = vi_{ipt} \widetilde{pe}_{ipt} \tag{10}$$

$$\sum_k \sum_m \pi l_{ikmpt} = vl_{ipt} \widetilde{pe}_{ipt} \tag{11}$$

$$vr_{ipt} + vi_{ipt} + vl_{ipt} = 1 \tag{12}$$

$$\sum_j \sum_t \sum_r x_{frjt} \le \alpha \tag{13}$$

$$\sum_{j}\sum_{r} x_{frjt} \leq \alpha' \tag{14}$$

$$\sum_{l}\sum_{t}\sum_{r} y_{frlt} \leq \beta \tag{15}$$

$$\sum_{l}\sum_{r} y_{frlt} \leq \beta' \tag{16}$$

$$\sum_{k}\sum_{t}\sum_{r} z_{frkt} \leq \gamma \tag{17}$$

$$\sum_{k}\sum_{r} y_{frkt} \leq \gamma' \tag{18}$$

$$\pi_{ijmpt}, \pi r_{ilmpt}, \pi l_{ikmpt}, \pi a_{jkmpt}, vi_{ipt}, vr_{ipt}, vl_{ipt} \in int^{+} \tag{19}$$

$$x_{frjt}, y_{frlt}, z_{frkt} \in \{0,1\} \tag{20}$$

Diverse costs related to the solid waste processing supply chain are represented in Eq. (1). The installation cost of incineration, recycling, and landfill centers is indicated in the first, second, and third terms. The fourth one indicates the waste collection cost at the solid waste management site. The cost associated with waste transportation from the solid waste management site to the incineration facility in addition to waste incineration cost is represented in the fifth term. The sixth one indicates the cost of waste transportation from solid waste management to a recycling facility and waste recycling cost. The cost of waste transportation from solid waste management site to landfill facility and waste landfill cost is denoted in the seventh term. Ultimately, both the cost of ash disposal and the cost of ash conveyed from the incineration facility to the landfill facility are represented in the eighth term.

Furthermore, Eq. (2) denotes the estimation of CO_2 emissions for the different disaster waste processes. Total CO_2 emissions during disaster waste collection at solid waste management site are determined in the first term. The second one represents the CO_2 emissions during waste incineration and disaster waste from the solid waste management site to an incineration facility. Likewise, the next three terms indicate the total CO_2 emissions during recycling, waste landfill, and ash landfill operations, respectively. Besides, Eq. (3) shows the total number of job opportunities provided during disaster waste processing operations. These opportunities provided during disaster waste incineration, recycling, and landfill processes are represented in the three terms of Eq. (3), respectively. The capacity constraints of the incineration, recycling, and landfill facilities are depicted in constraints (4), (5), and (6), respectively. Constraint (7) guarantees that all the waste from each solid waste management site has been processed. Constraint (8) depicts the quantity of ash (produced by incineration) to be conveyed from incineration facilities to the landfill centers. The total quantity of disaster waste to be recycled, incinerated, and landfilled at each TDDMS are determined in constraints (9), (10), (11), and (12), respectively. Constraints (13), (15), and (17) represent various upper bounds for the number of permanent incinerations, recycling, and landfill facilities to be installed in each area, respectively. Similarly, three different upper bounds are considered for the number of temporary incinerations, recycling, and landfill facilities to be installed in each area in constraints (14), (16), and (18), respectively. Ultimately, the respective decision variables' domain is determined in constraints (19) and (20).

III. SOLUTION APPROACH

To deal with the uncertainties in the proposed multi-objective mixed-integer linear programming model, a possibilistic programming approach, that is a fuzzy goal programming technique, is presented. Considering $\tilde{B}$ as a triangular fuzzy number, Eq. (21) will be taken into account as the membership function of $\tilde{B}$:

$$\mu_{\tilde{B}}(x) = \begin{cases} \dfrac{x-b^p}{b^m-b^p}, & b^p \le x \le b^m \\ 1 & x = b^m \\ \dfrac{b^o-x}{b^o-b^m}, & b^m \le x \le b^o \\ 0, & x \le b^p \ or \ x \ge b^o \end{cases} \tag{21}$$

The fuzzy mathematical programming model, whose parameters are considered as fuzzy triangular numbers, is assumed to be as follows:

$$Min\ Z = \tilde{b}^t$$

S.t.

$$\tilde{a}_i x \ge \tilde{c}_i \qquad \forall (i = 1,2,3,\dots,l)$$

$$\tilde{a}_i x = \tilde{d}_i \qquad \forall (i = l+1,\dots,m)$$

$$x \ge 0 \tag{22}$$

It should be noted that some factors in this study are only assumed to be uncertain parameters. The presented approach is applied for defuzzification to construct an equivalent crisp model for a fuzzy multi-objective model (Mousavi et al., 2013; Vahdani et al., 2012). Using the presented approach in Jiménez et al. (2007), the equivalent crisp α-parametric model of the model (22) will be as follows:

$$\min\ [EV(\tilde{B})]x$$

Subject to

$$((1-\alpha)E_2^a + \alpha E_1^a)x \ge \alpha E_2^c + \left(1-\alpha\right)E_1^c \qquad i = 1,2,\dots,l$$

$$((1-\frac{\alpha}{2})E_2^a + \frac{\alpha}{2}E_1^a)x \ge \frac{\alpha}{2}E_2^c + \left(1-\frac{\alpha}{2}\right)E_1^c \qquad i = l+1,\dots,m$$

$$(\frac{\alpha}{2}E_2^a + (1-\frac{\alpha}{2})E_1^a)x \le \left(1-\frac{\alpha}{2}\right)E_2^c + \frac{\alpha}{2}E_1^c \qquad i = l+1,\dots,m$$

$$x \ge 0 \tag{23}$$

Where

$$EV(\tilde{B}) = \frac{b^p + 2b^m + b^o}{4}$$

$$E_1^a = \frac{1}{2}(a^p + a^m)$$

$$E_1^a = \frac{1}{2}(a^m + a^o)$$

$$E_2^c = \frac{1}{2}(c^p + c^m)$$

$$E_2^c = \frac{1}{2}(c^m + c^o).$$

With the above in mind, the equivalent crisp α-parametric model of the proposed fuzzy multi-objective mixed-integer linear programming model will be as follows:

Objective functions: (1)-(3)

S.t.

$$\sum_i \sum_m \pi_{ijmpt} \leq ((1-\alpha)E_2^{\lambda_{jpr}} + \alpha E_1^{\lambda_{jpr}})x_{frjt} \qquad ;\forall j,p,t,f,r \qquad (24)$$

$$\sum_i \sum_m \pi r_{ilmpt} \leq ((1-\alpha)E_2^{\lambda_{lpr}} + \alpha E_1^{\lambda_{lpr}})y_{frlt} \qquad ;\forall l,p,t,f,r \qquad (25)$$

$$\sum_i \sum_m \pi l_{ikmpt} + \sum_j \sum_m \pi a_{jkmpt} \leq ((1-\alpha)E_2^{\lambda_{kpr}} + \alpha E_1^{\lambda_{kpr}})z_{frkt} \qquad ;\forall k,p,t,f,r \qquad (26)$$

$$(\left(1-\frac{\alpha}{2}\right)E_2^{pe_{ipt}} + \frac{\alpha}{2}E_1^{pe_{ipt}}) - \sum_j \sum_m \pi_{ijmpt} - \sum_l \sum_m \pi r_{ilmpt} - \sum_k \sum_m \pi_{ikmpt} \geq 0 \qquad ;\forall i,p,t \qquad (27)$$

$$(\left(1-\frac{\alpha}{2}\right)E_1^{pe_{ipt}} + \frac{\alpha}{2}E_2^{pe_{ipt}}) - \sum_j \sum_m \pi_{ijmpt} - \sum_l \sum_m \pi r_{ilmpt} - \sum_k \sum_m \pi_{ikmpt} \leq 0 \qquad ;\forall i,p,t \qquad (28)$$

$$\sum_k \sum_m \pi a_{jkmpt} \geq \sum_i \sum_m (\left(1-\frac{\alpha}{2}\right)E_1^{pe_{ipt}} + \frac{\alpha}{2}E_2^{pe_{ipt}})\pi_{ijmpt} \qquad ;\forall j,p,t \qquad (29)$$

$$\sum_k \sum_m \pi a_{jkmpt} \leq \sum_i \sum_m (\left(1-\frac{\alpha}{2}\right)E_2^{pe_{ipt}} + \frac{\alpha}{2}E_1^{pe_{ipt}})\pi_{ijmpt} \qquad ;\forall i,p,t \qquad (30)$$

$$\sum_l \sum_m \pi r_{ilmpt} \geq vr_{ipt}(\left(1-\frac{\alpha}{2}\right)E_1^{pe_{ipt}} + \frac{\alpha}{2}E_2^{pe_{ipt}}) \qquad ;\forall i,p,t \qquad (31)$$

$$\sum_l \sum_m \pi r_{ilmpt} \leq vr_{ipt}(\left(1-\frac{\alpha}{2}\right) E_2^{pe_{ipt}} + \frac{\alpha}{2} E_1^{pe_{ipt}}) \qquad ; \forall i, p, t \tag{32}$$

$$\sum_j \sum_m \pi_{ijmpt} \geq vi_{ipt}(\left(1-\frac{\alpha}{2}\right) E_1^{pe_{ipt}} + \frac{\alpha}{2} E_2^{pe_{ipt}}) \qquad ; \forall i, p, t \tag{33}$$

$$\sum_j \sum_m \pi_{ijmpt} \leq vi_{ipt}(\left(1-\frac{\alpha}{2}\right) E_2^{pe_{ipt}} + \frac{\alpha}{2} E_1^{pe_{ipt}}) \qquad ; \forall i, p, t \tag{34}$$

$$\sum_k \sum_m \pi l_{ikmpt} \geq vl_{ipt}(\left(1-\frac{\alpha}{2}\right) E_1^{pe_{ipt}} + \frac{\alpha}{2} E_2^{pe_{ipt}}) \qquad ; \forall i, p, t \tag{35}$$

$$\sum_k \sum_m \pi l_{ikmpt} \leq vl_{ipt}(\left(1-\frac{\alpha}{2}\right) E_2^{pe_{ipt}} + \frac{\alpha}{2} E_1^{pe_{ipt}}) \qquad ; \forall i, p, t \tag{36}$$

Constraints (12)-(20)

Further details concerning the method can be found in Jiménez et al. (2007). A multi-choice goal programming (MCGP) approach called PM1 is utilized to solve this crisp multi-objective mixed-integer linear programming (MOMILP) model, which is presented in Chung et al. (2018) and is based on the following definitions:

Definition A. There exist two feasible points, namely x and y. Here, x dominates y if $\{z_k(x) \geq z_k(y)$ and $w_s(x) \leq w_s(y), \forall k, s\}$ and $\{z_j(x) > z_j(y)\}$for some j, or $w_t(x) < w_t(y)$ for some t, we illustrate it by $x > y$.

Definition B. x as a possible point is regarded as a Pareto-optimal solution if its criterion vector is not dominated by the criterion vector of any point in the feasible region. Meaning that, x is considered as a Pareto-optimal solution if there is not any possible point y such that $y > x$.

Goal programming has been extensively utilized in several multi-objective problems. The membership function is regarded as an essential element of fuzzy theory. The relationship between goal programming and membership function is addressed. Moreover, goal programming is applied to formulate membership function to benefit from the merits mentioned above.

The membership function is rewritten as:

$$\mu_k(x) = \frac{z_k(x) - z_k^-}{z_k^* - z_k^-} = \frac{z_k^* - z_k^- - z_k^* + z_k(x)}{z_k^* - z_k^-} = 1 - \frac{z_k^* - z_k(x)}{z_k^* - z_k^-}. \tag{37}$$

The average membership function with weight w_k is maximized to have

$$Max \sum_{k=1}^{l} w_k\, \mu_k(x) = Max \sum_{k=1}^{l} w_k(1 - \frac{z_k^* - z_k(x)}{z_k^* - z_k^-}) = \sum_{k=1}^{l} w_k + Max\{-\sum_{k=1}^{l} w_k \frac{z_k^* - z_k(x)}{z_k^* - z_k^-}\} \tag{38}$$

The aforementioned objective function is equivalent to minimizing $\sum_{k=1}^{l} w_k \frac{z_k^* - z_k(x)}{z_k^* - z_k^-}$. For $\frac{z_k^* - z_k(x)}{z_k^* - z_k^-}$, $k = 1, , \dots, l,$ with no loss of generality, $z_k^- = 0$ and $z_k^* = g_k = BN$ are determined.

Where BN is a big positive value? Thus, $\frac{g_k - z_k(x)}{\Delta z_k}$ is regarded in which Δz_k is a constant value. Also, $\Delta z_1 = \Delta z_2 = \Delta z_3 = \cdots = \Delta z_l = \Delta z$ and $g_k - z_k(x) = d_k^-$ are taken into account.

Consider the following model for the implementation of the PM1 approach in the proposed model.

$$\text{Min} \sum_{k=1}^{l} (\alpha_k d_k^- + \omega_k e_k^-) + \sum_{s=1}^{r} (\beta_s d_s^+ + \delta_s e_s^+) \tag{39}$$

$s.t.$

$$Z_k(x) + d_k^- = \varphi_k \quad k = 1,2,\dots,l \tag{40}$$

$$\varphi_k + e_k^- = g_{k,max} \quad k = 1,2,\dots,l \tag{41}$$

$$w_s(x) - d_s^+ = \varphi_s \quad s = 1,2,\dots,r \tag{42}$$

$$\varphi_s - e_s^+ = g_{s,min} \quad s = 1,2,\dots,r \tag{43}$$

$$g_{k,min} \le \varphi_k \le g_{k,max}, g_{s,min} \le \varphi_s \le g_{s,max} \tag{44}$$

$$d_k^-, e_k^-, d_s^+, e_s^+ \ge 0, k = 1,2,\dots,l, s = 1,2,\dots,r \tag{45}$$

Where d_k^- and d_s^+ are the negative and positive deviations attached to ($Z_k(x) - \varphi_k$) and ($w_s(x) - \varphi_s$) in Eqs. (40) and (42); $\varphi_k$and φ_s are continuous variables; e_k^- and e_s^+ are negative and positive deviations attached to ($\emptyset_k - g_{k,max}$) and ($\varphi_s - g_{s,min}$) in Eqs. (41) and (43); $g_{k,max}$ and $g_{s,min}$ are the upper and lower bound value of the goal target; α_k> 0 and β_s> 0 are the weights attached to the deviations of d_k^- and d_s^+ ; ω_k> 0 are the upper and lower bound value of the goal target; δ_s> 0 are the weights attached to the deviations e_k^- and e_s^+ ; $g_{k,max}$ ($g_{s,min}$) is the upper(lower) bound of the k (s) the goal.

With the above in mind, the implementation of the approach mentioned above in the proposed mathematical model is as follows:

$$\text{Min}(\alpha_1 d_3^- + \alpha_2 e_3^-) + (\beta_2 d_1^+ + \delta_2 e_1^+) + (\beta_3 d_2^+ + \delta_4 e_2^+) \tag{46}$$

$s.t.$

$$Z_3(x) + d_3^- = \varphi_3 \tag{47}$$

$$\varphi_3 + e_3^- = g_{3,max} \tag{48}$$

$$w_s(x) - d_s^+ = \varphi_s \quad s = 1,2 \tag{49}$$

$$\varphi_s - e_s^+ = g_{s,min} \quad s = 1,2 \tag{50}$$

$$g_{3,min} \leq \varphi_k \leq g_{3,max}, g_{s,min} \leq \varphi_s \leq g_{s,max} \tag{51}$$

Constraints (12)-(20),(24)-(36)

$$d_3^-, e_3^-, d_s^+, e_s^+ \geq 0, s = 1,2. \tag{52}$$

IV. CASE STUDY

Generally speaking, Iranian municipalities have been in charge of different waste management activities since 1903. A case study related to municipal solid waste management in Tehran is employed therein to demonstrate the introduced model's efficiency. As a northern city and capital of Iran, Tehran is one of the most densely populated cities in the world and one of the biggest cities in Iran. This city is ranked twenty-third in order of population and sixteenth in order of density. The enormous amount of municipal solid waste produced per day, which needs to be gathered and disposed, is a severe concern of Tehran's municipal solid waste management system.

In this research, an urban solid waste management system is presented for 15 urban areas of Tehran. Due to the confidentiality of the information, the name of the candidate facilities to be established is withheld from the readers. Since a significant amount of municipal solid waste consists of paper and glass, they have been investigated in this study. One of the essential model inputs is the amount of the generated waste, regarding two waste types, namely paper and glass, in 15 urban areas of Tehran in three periods of time is considered a triangular fuzzy number. Bounds, low estimate, best estimate, and a high estimate of this triangular fuzzy number are presented in Tables II-IV, respectively. After entering other case study parameters, the model is implemented through the CPLEX Solver in GAMS 24.1.3.

TABLE II. AMOUNT OF GENERATED SOLID WASTES (LOW ESTIMATE)

Region, solid waste types (paper, glass) \ Period	*1*	*2*	*3*
1, paper	320	640	480
1, glass	336	656	496
2, paper	240	640	560
2, glass	252	652	576
3, paper	240	560	400
3, glass	248	576	416
4, paper	240	320	280
4, glass	252	333	296
5, paper	240	560	440
5, glass	248	572	456
6, paper	240	880	640
6, glass	256	912	656
7, paper	240	480	360
7, glass	257	492	376
8, paper	240	480	360

CONTINUE TABLE II. AMOUNT OF GENERATED SOLID WASTES (LOW ESTIMATE)

Region, solid waste types (paper, glass) \ *Period*	*1*	*2*	*3*
8, glass	252	488	376
9, paper	320	400	360
9, glass	336	408	376
10, paper	160	320	240
10, glass	176	328	256
11, paper	240	400	352
11, glass	248	408	368
12, paper	320	480	444
12, glass	328	496	460
13, paper	160	400	268
13, glass	176	408	284
14, paper	160	320	276
14, glass	176	336	292
15, paper	160	400	280
15, glass	168	412	292

TABLE III. AMOUNT OF GENERATED SOLID WASTES (BEST ESTIMATE)

Region, solid waste types (paper, glass) \ *Period*	*1*	*2*	*3*
1, paper	400	800	600
1, glass	420	820	620
2, paper	300	800	700
2, glass	315	815	720
3, paper	300	700	500
3, glass	310	720	520
4, paper	300	400	350
4, glass	315	417	370
5, paper	300	700	550
5, glass	310	715	570
6, paper	300	1100	800
6, glass	320	1140	820
7, paper	300	600	450
7, glass	322	615	470

CONTINUE TABLE III. AMOUNT OF GENERATED SOLID WASTES (BEST ESTIMATE)

Region, solid waste types (paper, glass) \ *Period*	*1*	*2*	*3*
8, paper	300	600	450
8, glass	315	610	470
9, paper	400	500	450
9, glass	420	510	470
10, paper	200	400	300
10, glass	220	410	320
11, paper	300	500	440
11, glass	310	510	460
12, paper	400	600	555
12, glass	410	620	575
13, paper	200	500	335
13, glass	220	510	355
14, paper	200	400	345
14, glass	220	420	365
15, paper	200	500	350
15, glass	210	515	365

TABLE IV. AMOUNT OF GENERATED SOLID WASTES (HIGH ESTIMATE)

Region, solid waste types (paper, glass) \ *Period*	*1*	*2*	*3*
1, paper	520	1040	780
1, glass	546	1066	806
2, paper	390	1040	910
2, glass	409	1060	936
3, paper	390	910	650
3, glass	403	936	676
4, paper	390	520	455
4, glass	409	542	481
5, paper	390	910	715
5, glass	403	929	741
6, paper	390	1430	1040
6, glass	416	1482	1066
7, paper	390	780	585

CONTINUE TABLE IV. AMOUNT OF GENERATED SOLID WASTES (HIGH ESTIMATE)

Region, solid waste types (paper, glass) / *Period*	*1*	*2*	*3*
7, glass	418	800	611
8, paper	390	780	585
8, glass	410	793	611
9, paper	520	650	585
9, glass	546	663	611
10, paper	260	520	390
10, glass	286	533	416
11, paper	390	650	572
11, glass	403	663	598
12, paper	520	780	721
12, glass	533	806	447
13, paper	260	650	434
13, glass	286	663	462
14, paper	260	520	489
14, glass	286	546	475
15, paper	260	650	455
15, glass	273	669	474

V. RESULTS AND SENSITIVITY ANALYSIS

After implementing the model through the CPLEX Solver in GAMS 24.1.3, the three considered objective functions' optimal solutions, namely maximizing job opportunities and minimizing costs and carbon emissions, are obtained.

A. Numerical results

These Pareto optimal solutions are listed in Table V. Furthermore, the trade-off between the third objective function, that is, job opportunities, and the second objective function, that is, CO_2 emissions, are represented in Fig. 2. It should also be noted that the second and the third objective functions with 15 Pareto optimal solutions are only taken into account as an example in both Table V and *Fig.* 2. As shown in Table V, the second objective function is increased from 1270671.62 to 1358755.92 by increasing the third objective function from 9653.1 to 11455.85. Meaning that, with a 15.73% increase in job opportunities, carbon emission grows 6.48%. Therefore, there is a direct relationship between them, meaning that the second objective function, carbon emission, is increased by increasing the third objective function, job opportunities.

TABLE V. PARETO OPTIMAL SOLUTIONS OF THE SECOND AND THIRD OBJECTIVE FUNCTIONS

OF / *P.S* [1]	*Z2(CO2 emission)*	*Z3(Job opportunities)*
1	1270671.62	9653.1
2	1275390.52	9782.84
3	1282512.85	9893.47
4	1290323.44	10140.18
5	1297664.4	10254.02
6	1306251.9	10374.2
7	1308792.96	10527.2
8	1313493.99	10614.57
9	1321661.28	10734.75
10	1330074.15	10854.94
11	1333358.6	11067.96
12	1334680.54	11095.3
13	1342241.57	11215.49
14	1350942.65	11335.67
15	1358755.92	11455.85

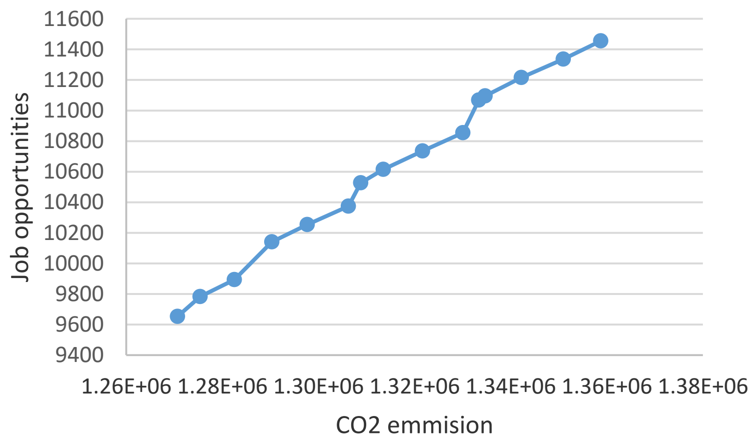

Fig. 2. The trade-off between the second and third objective functions

B. Sensitivity analysis

A sensitivity analysis is performed on the proposed solution approach to analyze the three objective functions' changes considering different weights determined by decision-makers and various α levels. Table VI shows the first, second, and third objective functions considering various α levels. As illustrated, by increasing α level from 0.1 to 0.7, the amount of generated waste is increased, which leads to an increase in the values of objective functions.

1 . Pareto solutions

TABLE VI. THE VALUES OF OBJECTIVE FUNCTIONS IN DIFFERENT A LEVELS

OF / $\alpha - level$	*Z1 (Cost)*	*Z2 (CO2 emission)*	*Z3 (Job opportunities)*
0.1	7.63E+06	1.23E+06	8626.682
0.2	7.70E+06	1.24E+06	8744.79
0.3	7.78E+06	1.25E+06	8862.899
0.4	7.86E+06	1.25E+06	8981.007
0.5	7.93E+06	1.26E+06	9099.15
0.6	8.01E+06	1.27E+06	9217.224
0.7	8.08E+06	1.28E+06	9335.332

Moreover, the influence of changes in goal programming coefficients on the values of objective functions is evaluated in Table VII. It is worth noting that some of these results are only depicted as an example in *Figs.* 3- 5. Meaning that, α_1 and α_2 for the first objective function, β_1 and β_2 for the third objective function, β_3 and β_4 for the second objective function are only illustrated in these figures, respectively. While changing α_1 and α_2 for the first objective function, β_1 and β_2 for the third objective function, β_3 and β_4 for the second objective function, both α level and other goal programming coefficients are considered to be constant and equal to 0.5.

As it can be observed, the first objective function (minimizing cost) is increased by increasing α_1 from 0.1 to 0.5 and decreasing α_2 from 0.9 to 0.5. The second objective function (minimizing CO_2 emissions) is decreased by increasing β_3 from 0.1 to 0.5 and decreasing β_4 from 0.9 to 0.5. Ultimately, the third objective function (job opportunities) is decreased by increasing β_1 from 0.1 to 0.5 and decreasing β_2 from 0.9 to 0.5.

TABLE VII. THE VALUES OF OBJECTIVE FUNCTIONS CONSIDERING DIFFERENT GOAL PROGRAMMING COEFFICIENTS

OF / α_1, α_2	*Z1 (Cost)*	*Z2 (CO2 emission)*	*Z3 (Job opportunities)*
0.1,0.9	7.93E+06	1.26E+06	9114.115
0.2,0.8	7.95E+06	1.26E+06	9169.225
0.3,0.7	8.12E+06	1.30E+06	9539.385
0.4,0.6	8.53E+06	1.35E+06	10201.907
0.5,0.5	8.75E+06	1.36E+06	10479.214
OF / β_1, β_2	*Z1(Cost)*	*Z2(CO2 emission)*	*Z3(Job opportunities)*
0.1,0.9	9.37E+06	1.38E+06	10967.232
0.2,0.8	9.37E+06	1.38E+06	10967.232
0.3,0.7	9.15E+06	1.36E+06	10817.892
0.4,0.6	9.04E+06	1.36E+06	10731.496
0.5,0.5	8.75E+06	1.36E+06	10479.214
OF / β_3, β_4	*Z1(Cost)*	*Z2(CO2 emission)*	*Z3(Job opportunities)*
0.1,0.9	8.79E+06	1.37E+06	10520.208
0.2,0.8	8.77E+06	1.37E+06	10506.208
0.3,0.7	8.77E+06	1.37E+06	10506.208
0.4,0.6	8.76E+06	1.36E+06	10492.389
0.5,0.5	8.75E+06	1.36E+06	10479.214

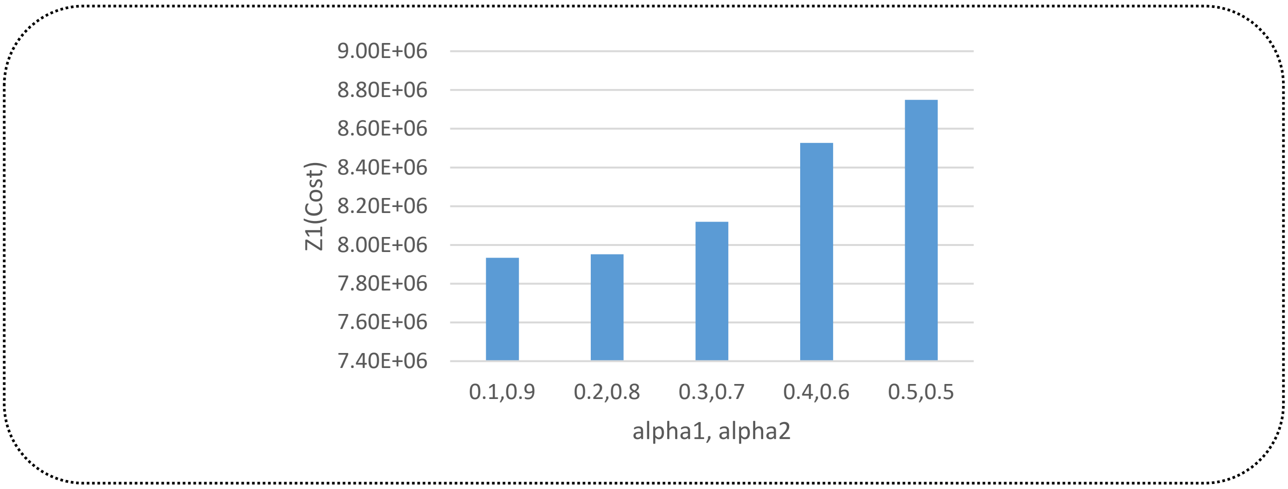

Fig. 3. The trend of the first objective function based on the changes in α_1 and α_2

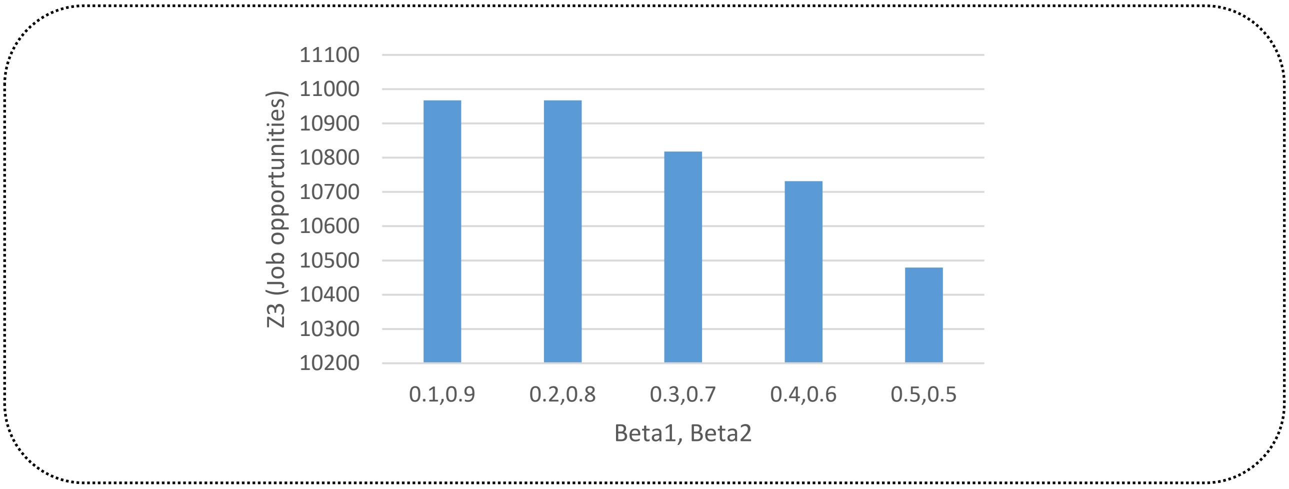

Fig. 4. The trend of the third objective function based on the changes in β_1 and β_2

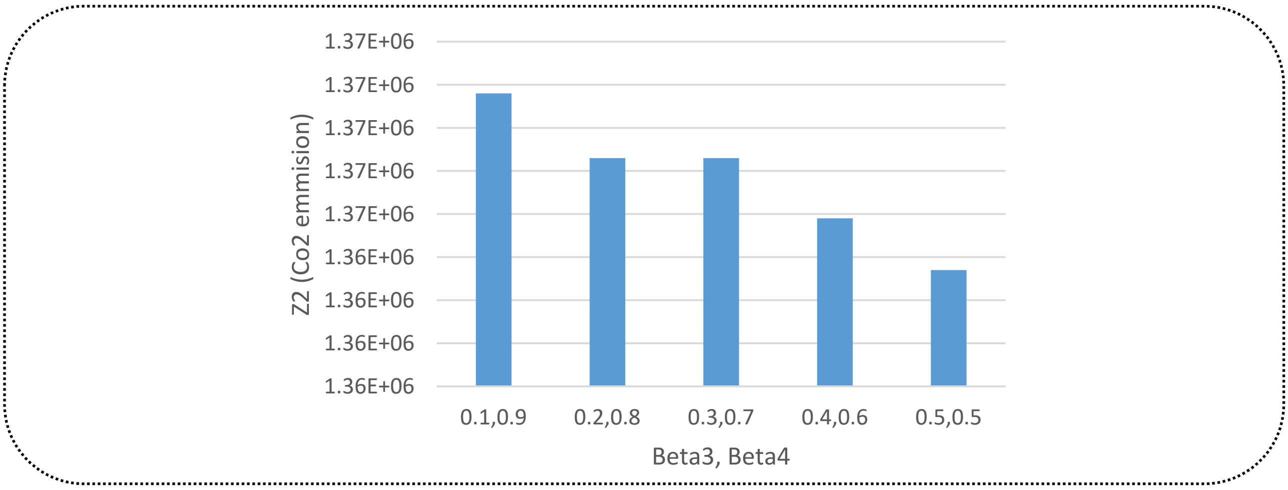

Fig. 5. The trend of the second objective function based on the changes in β_3 and β_4

VI. CONCLUSION

Given the importance of solid waste management, a mixed-integer linear programming model with multiple objectives for waste management was presented in an uncertain environment. Concerning the identified literature gaps through investigating the prior studies, multi-mode transportation, permanent and temporary facilities, and two municipal solid waste types were assumed simultaneously in the proposed model. The presented approach in Jiménez et al. (2007) was utilized to cope with the existing uncertainties. The goal programming approach was applied due to the considered multi-objective equivalent crisp model and the importance of decision-makers' opinions. A case study was employed in fifteen urban areas of Tehran to demonstrate the applicability of the model. As illustrated, the second objective function was increased from 1270671.62 to 1358755.92 by increasing the third objective function from 9653.1 to 11455.85. Meaning that, with a 15.73% increase in job opportunities, carbon emission grows 6.48%. Also, a sensitivity analysis was performed. In this way, the proposed mathematical model was implemented, and the individual results were appraised considering different α levels and goal programming coefficients. As expected, the objective functions were increased by increasing the considered α levels. Even though various novelties were presented in this paper, there are different other ways by which the model can be extended. For instance, hazardous wastes and particular facilities for them can be assumed in the mathematical model. Besides, considering wet wastes can be interesting for future research. Moreover, using other approaches can be taken into account to solve the multi-objective mathematical model.

ACKNOWLEDGMENT

The authors would like to thank anonymous referees for their valuable comments on the initial version of this study for the improvements.

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