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Locating incineration facilities to minimize environmental effects and visual pollution in Tehran mega city

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A B S T R A C T

Municipal solid waste management is one of the main challenges in mega cities. Consequences of landfilling and importance of using alternative energies contribute to the popularity of incineration facilities for city authorities. This article tries to determine the location and allocation decisions on landfills and incineration facilities regarding social and environmental effects. The proposed model minimizes revenue of selling recovered energy and minimizes visual pollution impacts. In addition, the environmental impacts of incineration and landfilling operations are considered as part of constraints. Using the data of Tehran's waste management organization, numerical results show the number of active transfer stations and traffic reduce leading to an increase on waste collection network's efficiency. The results also show a decrease on the landfilling and the amount of hazardous methane emissions as well as an improvement on power and heat energy recovery.

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1. Introduction

During the past decades, one of the primary concern has been to figure out how to collect and dispose the booming amounts of municipal solid waste (MSW) along with the rapid urbanization and population growth. Developing countries are exposed to environmental and social impacts caused by the increase of waste generation due to the population growth (Guerrero et al., 2013). High costs of transportation and increasing attention to environmental and social effects have resulted in emerging transfer station facilities in waste collection system (Chatzouridis & Komilis, 2012). Risks of landfilling in addition to the importance of using alternative energies have contributed to the popularity of transfer stations equipped with incineration systems for city authorities (Alçada-Almeida et al., 2009). Around 130 million tons of municipal solid waste are combusted annually in over 600 waste-to-energy facilities globally that produce electricity and heat (U.S. EPA[1] Report, 2011).

[1] U.S. Environmental Protection Agency

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In Iran, about 99.5% of generated energies are still supplied with non-renewable resources (World Bank, 2011). In this regard, existing documents in Iran such as country's vision, law for modification of energy consumption pattern and Iran's sixth development plan emphasize on substituting non-renewable energies with alternative ones in different ways. Therefore, importance of using alternative energies beside the increasing amount of waste generation in Iran's mega cities has contributed to the popularity of incineration method to related organizations. Incineration facility as a transfer station operates the same as hub facility that operations such as unloading, combusting and loading ash in semi-trailers happen in it.

The high cost of investment on incineration facilities and their short/long term environmental and social effects are counted as necessities of doing this research. The authors of this paper have tried to use the proposed model and its results to identify the decision-maker's optimal strategy for facility location in Tehran's waste collection network and improve the status of stakeholders in this area.

In this paper, environmental and social impacts are considered as a mathematical model in addition to the cost factor in locating landfills and incineration facilities. For this purpose, a multi-objective optimization problem is built. The first objective function calculates the total transportation cost over all pairs and the fixed cost of establishing incineration facilities and their annual operational cost. In addition, it considers the income of selling recovered energy as power, heat or combination of them in incineration facilities.

The second objective function minimizes the maximum amount of visual pollution over all incinerators and landfills in order to achieve a fair situation for all of the city habitants. One of the important issues in the field of urban planning is visual comfort which should be considered to create suitable urban landscape. Heterogeneous visual elements with the environment or the accumulation of visual elements are called visual pollution that is often in metropolitan cities all over the world. The effects of this phenomenon such as mental distress, urban landscape confusion and behavioural disorders are increasing with the passage of time which reduces work efficiency among citizens (Ogawa & Shibaska, 2002).

Visual pollution is a new concept and has no certain and limited factors (Salehi, 2008). Uncollected waste along streets, waste collection trucks, undesirable facilities including landfills and incineration facilities are the visual pollution factors. In addition, the construction of the hubs creates the traffic effects near these facilities known as hubbing effects (Zanjirani Farahani et al., 2013). Hubbing effects and vehicle's waiting around the incineration facilities can also be considered as another component of visual pollution. By reviewing the existing articles in the literature, it seems that visual pollution in location modelling problems is not considered and its quantification is difficult. Moreover, landfilling waste and ash result in generating methane emissions. Also, incineration itself results in producing greenhouse gas emissions. These environmental effects are considered in model constraints.

To evaluate the applicability of this research, Tehran city with 22 districts as waste generation points is considered. Tehran's generated municipal solid waste per day reaches over 6,000 tons. In this study, it is assumed that collected waste is shipped from these points to incineration facilities and combusted. Then, the remained ash is carried to landfill by special vehicles. Also, the recovered energy during incineration is sold to target industries or utilized for other intended uses. However, some part of generated waste can be sent to landfills directly due to the capacity constraints and technical issues related to incineration facilities. In this regard, ten potential locations for incineration facilities and three ones for landfills have been introduced by experts. Optimal locations have been selected by mathematical modelling in order to reduce costs and visual pollution beside environmental and social impacts.

Locating the transfer station equipped with incineration systems is a new and welcomed issue for relevant organizations. The purpose of this paper is to provide an optimization approach to determine the location and allocation decisions of the incineration facilities in order to achieve the objectives of minimizing the costs simultaneously with social and environmental effects, by considering real world influencing conditions such as the income from recovery of energy in different types. Compromise programming method is used to deal with conflicting goals in this study. Also, the practical purpose of this article is to attempt to efficient management of incineration facilities by recognizing the social and environmental impact and the possible consequences of them in Tehran.

In summary, the most important new aspects of innovation in this research include:

- Development of a comprehensive model of waste collection network by integrating location and allocation problems or integration of strategic and tactical decisions on the location of landfills and waste transfer stations equipped incineration systems with energy recovery capabilities.
- Simultaneous consideration of economic, social and environmental impacts and proposing multi-objective optimization model instead of the traditional use of GIS and its combination with various methods of MCDM.
- Considering urban limitations and visual pollution originating from construction of landfills and incineration facilities in facility location problem to reduce urban disorder, mental illness and behavioural disorders in humans.
- Taking into account the environmental and social effects of operations in waste collection network segments and quantifying them in model.
- Confirmation of the applicability of the model by a case study in Tehran.
- Taking into account different types of recovered energy in incineration facilities in order to take advantage of alternative energy in accordance with the country's macro policies.
- Locating incineration facilities with a view to the hub location (new in aspect of theory and practice) which is rarely addressed in the field of urban management.

2. Literature review

Facility location has long been under discussion among researchers but they found in the 70s that not all facilities are pleasant and customers not necessarily always wish to be near the facilities. Facilities in waste collection network, which impose environmental risks and carry adverse consequences (Carrizosa et al., 1999; Coutinho-Rodrigues et al., 2012). Therefore, these facilities are considered as unpleasant facilities and nearby residents are not happy to be near of them and complain of health hazards, environmental pollution, noise pollution, visual pollution, traffic, etc. (Bovea et al., 2007). Waste management has a broad scope and optimizing operations of waste collection network seems a vital part of it. One of the ways to proper management of this network is to apply the transfer stations equipped with incineration systems and decreasing number of landfills. Locating facilities in waste collection network is among the most important decisions in this area.

Concept of middle points in order to minimize transport costs firstly stated by Marks and Libman in 1971. His model is a mixed integer transfer stations location problem with capacity constraints and taking into account the fixed costs of for all points and tries to find optimal location and allocation so that costs are minimized (Marks & Libman, 1971). This model is a basic model in the literature to locate transfer stations and other models are modified versions of it.

In order to locate waste transfer stations, extensive research has been done and the last two decades have brought new models and approaches. However, Eiselt et al. (2014) by review of articles published in this area focused more on locating transfer station and as can be seen in their work, the intersection of models in real-world studies in in the field of location - allocation of facilities in waste collection network is using mathematical optimization to find the approximate location for the proposed transfer stations and to apply multi-criteria decision-making tools for considering the different criteria. This trend has continued in recent studies as we can observe from the work accomplished by Ferri et al. (2015) in Brazil who applied MILP[2] and scenario based analysis to minimize costs in reverse logistic network for locating recovery facilities. Asefi et al. (2015) proposed a mathematical model for the municipal solid waste location-routing problem with intermediate transfer stations. Therefore, a limited number of studies have been performed on locating waste transfer stations using mathematical modelling and most papers in this field have selected optimal locations through the use of geographic information systems with multi-criteria decision making (Eskandari et al., 2012; Rafiee et al., 2011; Tavares et al., 2011).

Incineration facilities in waste collection network indirectly have used the existing hub concept in the literature and are counted as organized transport centres. Also, these hubs facilitate the transition and save time due to connections with a number of non- hub nodes (landfill and generation points). Thus, incineration facility location problem is a kind of hub location problem which aims at finding hubs and routs to send goods from sources to destinations so that the collection and distribution process is optimized. Hub location problem is a subset of network location optimization problem that includes locating hub facilities and designing of the network of these facilities. In general, the focus of most of the articles related to hub location problem has been on the initial modelling until 1980 and after that on modelling and optimization until 1990 and in recent years to provide advanced models and solution methods (Zanjirani Farahani et al., 2013).

Locating transfer stations as a hub in the waste collection network was proposed by Eiselt (2007) for the first time. Recently, Eiselt et al. (2015) expanded his research and believes that even though there is no flow of waste between transfer stations and they are different from the hub points in this regard, but in terms of the current discount factors and other similar functions, a similar approach with hub location problem can be considered for transfer station location problem. The use of hub facilities in distribution systems and connection networks makes a lot of environmental and social issues caused by the congestion at hubs called hubbing effects and the increase in the number of transfers, cost and time in some routes (Mohammadi et al., 2014). Although environmental and social effects are important to locate the nodes and arcs in hub location problem, only a small effort in locating these facilities with regard to social and environmental considerations have been made so far. To pay more attention to this research gap in the literature, a new approach can be seen in the area of facility location problem in waste collection network in recent years. For instance, Eiselt et al. (2015) provided an integer linear model that simultaneously locates landfills and transfer stations, determines their size and minimizes pollution and cost. Despite a long history of incineration facilities usage in cities around the world, the use of these facilities in Iran have been ignored for various reasons so far and possibility of using this method and exploring its different aspects should be addressed especially in populated cities such as Tehran. On the other hand, planning, design and operation of incineration facilities requires analysis of the negative effects related to lack of attention to city limitations. In the case of considering social issues in location models, it seems few studies have been accomplished by considering visual pollution caused by the establishing facilities in waste collection network although lots of research has been performed about visual comfort and urban landscape itself. In most parameters, the role of considering uncertainty of the real world in planning is undeniable. This issue exists in incineration facility location problem too and it is necessary to consider the uncertainty affecting the decisions in order to get closer to the real conditions of the problem's space. It is clear that not enough studies are available about facility location problem in waste collection network taking into account conflicting objectives. Most literature is focused on minimizing cost or distance travelled as criteria for the traditional objective functions but given the importance of environmental and social issues and to get closer to the real

[2] Mixed Integer Linear Programming

conditions, it is needed to give importance to social and environmental impacts such as visual pollution beside the usual economic aspect in modelling.

This paper tries to mention some of existing gaps in literature review and presents a mathematical multi objective model in incineration facilities location problem in a novel way.

3. Problem description

In general, a waste collection process, collected waste is sent to transfer stations by collection trucks and shipped to landfills by semi-trailers (Komilis, 2008). In this problem, there is a set of urban areas that generate waste every day. Generated wastes will be shipped to the landfills for processing, recycling and disposal through two ways. In the first way, the collected waste is sent directly to landfills. In the second, collected wastes are sent out first to incineration facilities and the remained ashes from combusting are transferred to landfill by special vehicles to reduce the total transportation frequency, time and cost. Also, the recovered energy during incineration as heat, power or a combination of them is sold out to target industries with different tariffs. In this network, landfilling waste and ash results in methane generation and shows the necessity of decreasing amount of landfilled waste. Also, incineration results in greenhouse gas emissions which should be limited by related standards. To better understand the problem, a view of the problem network is depicted in Fig. 1. The decisions derived from this study are expected to lead to finding the optimal location for incineration facilities that reduce transportation costs, risks related to the environmental effects and imposed visual pollution from incineration facilities and landfills on habitants as much as possible.

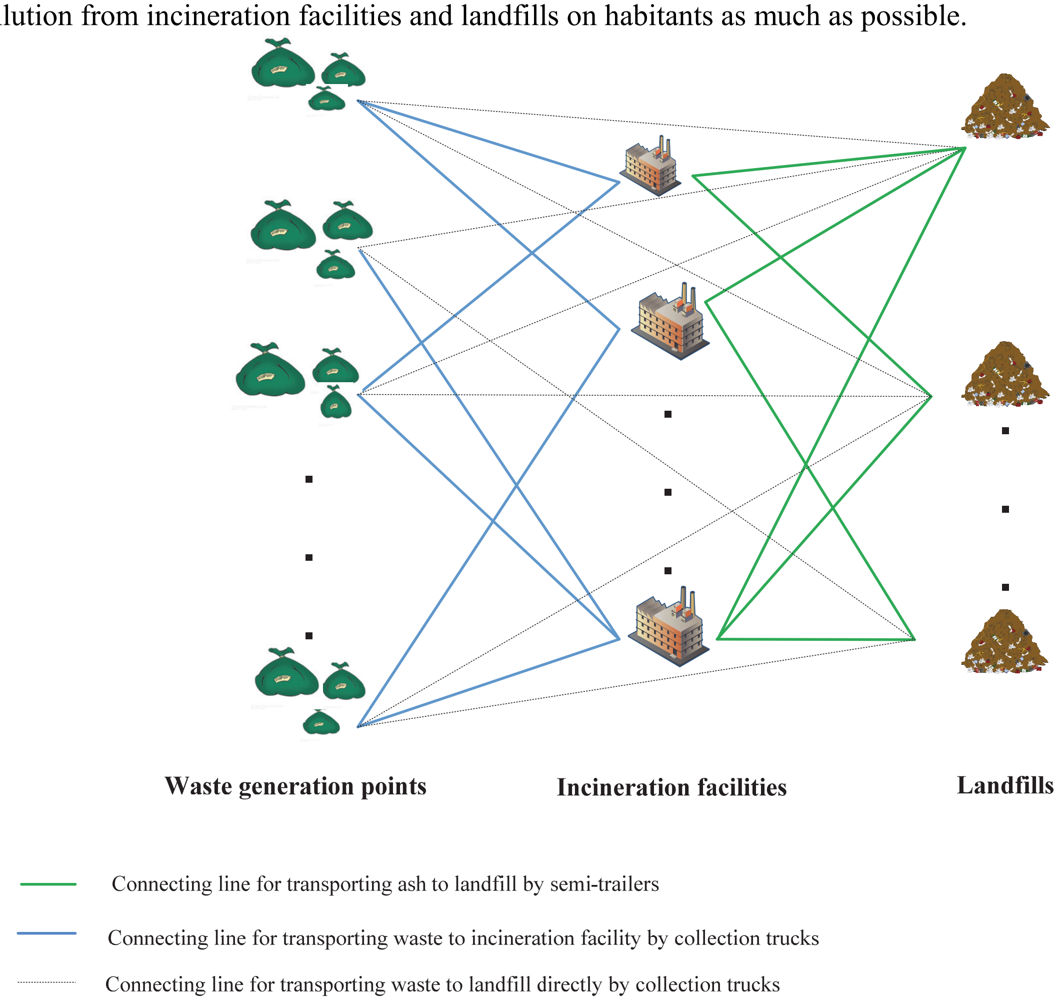

Fig. 1. A view of the network under study

The optimal site selection for incineration facilities and landfills is one of the most important decisions in waste management area that needs attention to various aspects affecting the issue. In order to determine optimal locations, the potential locations with necessary basic features are introduced by experts. Then, the described multi objective optimization problem is modelled mathematically and solved.

4. Formulation

Let us consider the under study network as shown in Fig. 1. In this paper, we address a new variant of waste collection network in which in addition to classical economic cost function, one other new objective function, by considering visual pollution, is also taken into account. The main assumptions used to formulate this problem are as follows:

- The maximum number of incineration facilities and landfills that must be located is pre-determined.
- A limited amount of flows can enter each landfill since there is determined capacity constraint.
- Lower and upper bound for entering flows to incineration facilities are determined.
- Waste is sent to the landfill directly or indirectly via incineration facilities.
- The problem is modelled under certainty in this paper.
- All demand of generation points should be meet.
- Waste will have decrease in amount and volume after combusting in incineration facility.
- Entering flows to incineration facility is equal to existing flow considering weight conversion factor.
- Maximum allowable emissions resulted from combusting are determined.
- Costs, budget of establishing facilities and profit of selling recovered energy is determined.
- Different used factors are all determined.
- Amount of emissions from each unit of waste and ash during operations is determined.
- Entering waste to a facility (incineration facilities or landfill) makes visual pollution.

The model formulated in this section has three layers: the waste generation points on the first layer, the incineration facilities on the second and the landfills on the third layer.

Notations Used in the model

Sets

- i Index of Waste generating regions $(i = 1 \ldots I)$
- k Index of incineration facilities $(k = 1 \ldots K)$
- j Index of landfills $(\mathrm{j} = 1 \ldots J)$
- g Set of energy recovery types as power, heat and combination of them $(g = 1 \ldots G)$

Parameters

- $\mathrm{a_{ij}}$ Euclidean distances between generation point i and landfill j (km)
- q_{ik} Euclidean distances between generation point i and incineration facility k (km)
- $\mathrm{e_{kj}}$ Euclidean distances between incineration facility k and landfill j (km)
- (Note that these distances are not used for cost computations, but for the assessment of pollution at individual customer sites)
- r Maximum number for landfills to establish
- m Maximum number for incineration facilities to establish
- h_k Maximum capacity limit for incineration facilities (ton)
- l_k Minimum capacity limit for incineration facilities needed to open a facility (ton)

- f_{kg} Fixed cost to establish and operate an incineration facility at site k with energy recovery type g ($)
- Δf_{kg} Volume-dependent annual cost ($/ton) to operate an incineration facility at site k with energy recovery type g ($)
- la_j Fixed cost to establish and operate a landfill at site j ($)
- c_{ij} Unit transportation costs ($/ton) to haul waste by collection truck from customer i directly to landfill j per distance unit and waste unit
- o_{ik} Unit transportation costs ($/ton) to haul waste by collection truck from customer i directly to incineration facility k per distance unit and waste unit
- t_{kj} Unit transportation costs to haul ash by transfer truck ($/ton) between incineration facility k and landfill j
- ϖ Amount of CO2 emission during incineration (ton gas/ton waste)
- υ Amount of NO2 emission during incineration (ton gas/ton waste)
- β Amount of NO2 emission during incineration (ton gas/ton waste)
- χ Amount of NO emission during incineration (ton gas/ton waste)
- ς Amount of NMVOCs3 (organic carbon) emission during incineration (ton gas/ton waste)
- $\rho_{\varpi}, \rho_{\upsilon}, \rho_{\beta}, \rho_{\chi}, \rho_{\varsigma}$ Global warming potential of emission (ton CO2/ton gas)
- η Amount of methane emission from landfilling waste (m3 gas/ton waste)
- ϕ Amount of methane emission from landfilling ash (m3 gas/ton ash)
- ψ Percentage of ash emitting methane
- γ Waste to ash converting factor
- n_i Number of inhabitants in region i; integer parameter
- γ Weight factor for converting waste to ash and energy
- Π_T, Π_L Visual pollution factors for landfills and incineration facilities (km2/ton waste*person)
- d_i Demand of each generation point i for collecting waste (ton)
- pr_g Profit of selling energy from incinerating each unit of waste with energy recovery type g ($)
- me Maximum allowable amount of emitted methane (m3 gas)
- co_2 Maximum allowable amount of emitted equal to CO2 gasses (ton gas)
- ca_j capacity of landfill at site j (ton)
- α Discount factor for using transfer stations equipped with incineration systems in transporting waste
- τ_g Waste to energy converting factor (energy unit/ton waste)
- b Dedicated budget for establishing facilities

Decision variables

- X_{ik} The waste quantity that is shipped from waste generation region i to and incineration facility k; real variable; (ton)
- W_{kj} The ash quantity that is shipped from incineration facility k to landfill j; real variable; (ton)

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3 Non-Methane Volatile Organic Compounds

- V_{ij} The waste quantity that is shipped directly from waste generation region i to landfill j; real variable; (ton)
- Z_{kg} Binary variable, 1 if the k-th incineration facility candidate point with energy recovery type g is opened, 0 otherwise;
- Y_j a zero-one variable that assumes the value of 1, if we open a landfill at site j
- ξ Maximum amount of visual pollution which is tried to be minimized to have a fair situation for habitants;

$$TC = \min\left(\sum_j la_j Y_j + \sum_i \sum_j c_{ij} a_{ij} V_{ij} + \alpha \sum_i \sum_k o_{ik} q_{ik} X_{ik} + \sum_k \sum_j t_{kj} e_{kj} W_{kj} + \sum_g \sum_k (f_{kg} Z_{kg} + \sum_i \Delta f_{kg} X_{ik}) \right. \tag{1}$$
$$\left. - \sum_i \sum_g \sum_k \tau_g pr_g X_{ik} \right)$$

$$TSI = \min \xi \tag{2}$$

$$\sum_j Y_j \le r \tag{3}$$

$$\sum_i \sum_k (\eta V_{ij} + \psi \phi W_{kj}) \le me \qquad \forall j \tag{4}$$

$$\sum_k \sum_i (\varpi \rho_\varpi + \upsilon \rho_\upsilon + \beta \rho_\beta + \chi \rho_\chi + \varsigma \rho_\varsigma) X_{ik} \le co_2 \tag{5}$$

$$d_i \le \sum_j V_{ij} + \sum_k X_{ik} \qquad \forall i \tag{6}$$

$$\sum_i V_{ij} + \sum_k W_{kj} \le ca_j Y_j \qquad \forall j \tag{7}$$

$$\sum_i X_{ik} \le h_k Z_{kg} \qquad \forall k, g \tag{8}$$

$$l_k Z_{kg} \le \sum_i X_{ik} \qquad \forall k, g \tag{9}$$

$$\gamma \sum_i X_{ik} = \sum_j W_{kj} \qquad \forall k \tag{10}$$

$$\sum_g Z_{kg} \le 1 \qquad \forall k \tag{11}$$

$$\sum_g \sum_k Z_{kg} \le m \tag{12}$$

$$\sum_j la_j Y_j + \sum_k \sum_g f_{kg} Z_{kg} \le b \tag{13}$$

$$\sum_i n_i [\sum_j \frac{(V_{ij} + \sum_k W_{kj})}{a_{ij}^2} \mu_L + \sum_k \frac{X_{ik}}{q_{ik}^2} \mu_T] \le \xi \tag{14}$$

$$0 \le V_{ij}, X_{ik}, W_{kj} \qquad \forall i, j, k \tag{15}$$

$$Y_j = \{0,1\} \qquad \forall j \tag{16}$$

$$Z_{kg} = \{0,1\} \qquad \forall k, g \tag{17}$$

The objective function (1), calculates the total transportation cost over all pairs, fixed cost of establishing landfills, the fixed cost of establishing incineration facilities and their annual operational costs based on flow. In addition, it considers the income of selling recovered energy in form of power, heat, and combination of them during incineration. The objective function (2), tries to minimize ξ, the maximum amount of visual pollution over all incinerators and landfills on all city habitants, as it has environmental and social consequences and a fair situation in these cases should be prepared for all habitants. This objective relates to constraint (14) in the following.

Constraints (3) enforce predetermined maximum number of landfills to establish. Constraints (4) enforce the permitted level of emitted methane from landfilling according to real world existing standards. Constraints (5) enforce the permitted level of emitted carbon dioxide equivalent emissions from combusting according to real world existing standards. Eq. (6) shows that all demand for waste collection should be met. Constraints (7) allow transporting waste from generation points to landfill only when a landfill is established on j and does not let the amount of entering waste to be more than landfill's capacity. Constraints (8) and (9) make sure that amount of entering waste to each incineration facility is not more than maximum capacity and these facilities can only be established if minimum determined amount of waste is entered. Eq. (10) state that the sum of all flows entering the incineration facility is equal to the sum of all the flows leaving that after combusting considering weight factor for converting waste to ash. Constraints (11) show in each node k at most one incineration facility with just one type of energy recovery can be established. Constraints (12) enforce maximum possible number of incineration facilities to establish based on available budget and other conditions. Constraints (13) enforce dedicated budget for establishing facilities in waste collection network. Constraints (14) relate to the second objective function and measure the visual pollution over all incinerators and landfills on all city habitants. It is reasonable that the amount of this type of pollution in each urban area is inversely related to the distance of each urban area from the location of the facility and this means that by reducing this distance, heterogeneous visual elements with environment and accumulation of visual elements increases and the visual pollution amount increases on that region. In this regard, the authors of this paper have used the distance as criteria to quantify this type of pollution. The First part shows the visual pollution from landfills and the second shows the visual pollution from all incineration facilities. Based on reality, the amount of visual pollution on city habitants has direct relationship with amount of entering waste to facilities and reverse relationship with square of distance from facilities. Finally, constraints (15) - (17) show the type of variables.

5. Compromise programming method to solve multi-objective optimization problem

After model formulation, it is needed to solve the problem with a multi- method. This section describes the method applied to facility location in waste collection network.Various methods exist for converting multi-objective programming to single-objective. Compromise programming has been used in this paper whose main idea is minimization of the distance between the ideal answer and expected one. For this purpose, first the nadir and ideal value are achieved for every objective function (Zeleny & Cochrane, 1973). The ideal value is achieved through optimizing model along each of the objective functions regardless of other functions and nadir value is achieved through optimizing in the opposite direction of any objective function. Another method for achieving nadir value can be used which is utilized in this research. To achieve the nadir value of any objective function, the value of objective functions is calculated after obtaining the ideal value for any objective function along the model and then, the nadir value is calculated for each function. The following equations show how to implement the calculations. If objective functions on the proposed model are Z_1, Z_2, their nadir and ideal values are Z_1^{ideal}, Z_2^{ideal}, Z_1^{nadir}, Z_2^{nadir} and also Z_{pq} is stating the value of q objective function on the basis of p objective function, we will have:

$$\begin{cases} Z_1^{ideal} = \min Z_1 \Rightarrow Z_{21} \\ Z_2^{ideal} = \min Z_2 \Rightarrow Z_{12} \end{cases} \Rightarrow \begin{cases} Z_1^{nadir} = Z_{12} \\ Z_2^{nadir} = Z_{21} \end{cases} \tag{18}$$

The difference values for each objective function from their ideal value in one objective function is minimized after determining above values. Also, the nadir and ideal difference were brought in order to normalize the objective functions in denominators and weight can be given to any objective function in order to determine the importance of each one. The following function can convert the model from multi –object to single –object in which Z and Ω_i are the values of single-object of objective function and the weight of any objective function, respectively.

$$Z = \Omega_1 \frac{Z_1 - Z_1^{ideal}}{Z_1^{nadir} - Z_1^{ideal}} + \Omega_2 \frac{Z_2 - Z_2^{ideal}}{Z_2^{nadir} - Z_2^{ideal}}. \tag{19}$$

This way, the multi-objective optimization problem can be transformed into a single-objective problem which can be solved with a commercial solver such as CPLEX. In this paper, the compromise programming method is used to solve the proposed problem.

In this paper, the proposed model has two competing objective functions subject to a set of constraints. The first function is the economical objective, whereas the second one is the environmental and social objective of the problem. The main problem can be transformed into problem (20) according to the basic principles of the compromise programming method. Problem (20) can be represented as follows and coded in GAMS to solve by CPLEX solver:

$$Z = \Omega_1 \frac{TC - TC^{ideal}}{TC^{nadir} - TC^{ideal}} + \Omega_2 \frac{TSI - TSI^{ideal}}{TSI^{nadir} - TSI^{ideal}}, \tag{20}$$

where Ω_1 and Ω_2 are the value of single-object of objective function and the weight of any objective function.

6. Case study

The proposed model for facility location in waste collection network is applied in city of Tehran, Iran. Currently, Tehran with over eleven million populations has more than 6000 tons generated waste each day. According to the latest classification, Tehran is divided into 22 districts. At present, the only landfill in Tehran is Aradkouh and 11 transfer stations are available. With a look on increasing population and the future needs, ten potential locations for establishing transfer stations equipped with incineration systems and three potential locations for landfills as in Fig. 2 have been suggested by experts. In addition to the assumptions referred to the proposed model, by considering the following points regarding model constraints on the environmental impact is essential. The incineration of municipal waste involves the generation of climate-relevant emissions. These are mainly emissions of CO_2 (carbon dioxide) as well as N_2O (nitrous oxide), NO_X (oxides of nitrogen) and organic C, measured as total carbon. Methane (CH_4) is not generated in waste incineration during normal operations. In this study, an existing method in the literature has been used to calculate the gases released during incineration operations. In this way, the gases emitted are changed to their carbon dioxide equivalent by global warming potential factors. In addition, different standards (strict, normal, and permissive) to determine the maximum permissible emissions from incineration systems exist that implementation of each one requires its own specific requirements (EPA report, 2011). In this study, normal standard in the relevant constraints of the proposed model is intended. Table 1 shows the amount of emissions and converting them to their CO_2-equivalent emission through global warming potential factor by multiplying the first and the second columns.

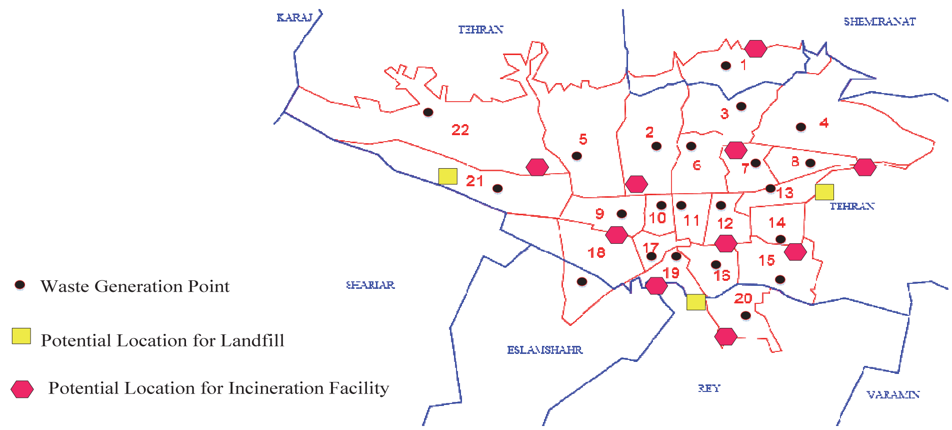

Fig. 2. The region and potential locations

Table 1
Gas emissions during incineration and CO2-equivalent emission[4]

Emitted gas	Total Emission (ton gas/ton waste)	GWP[5] (ton CO_2/ton gas)	Total emission CO_2-equivalent (ton CO_2/ton waste)
CO_2	0.415	1	0.415×1
N_2O	0.000011	310	310×0.000011
CH_4	0	21	0
CO	0.00275	3	3×0.00275
NO_X	0,0011	8	8×0.0011
TOC	0.00275	11	11×0.00275
SUM	-	-	23×0.46571

About the gas emissions in the landfill it can be said, the most dangerous emissions relates to methane since its greenhouse effect is several times more than carbon dioxide. Landfilling per ton of waste spreads 160 cubic meters methane and per ton of fly ash releases 30 cubic meters of methane. Of course, from the whole ash that goes to landfill, only a percentage of it (80%) called fly ash releases methane and it is included in the model. Different standards to determine the maximum permissible emissions from incineration systems exists that implementation of each one requires its own specific requirements (U.S. EPA Report, 2011). In this study, normal standard in the relevant constraints of the proposed model is intended.

7. Results and managerial analysis

Coding of the proposed model has been done in GAMS software and CPLEX solver has been used to determine the solutions. The accuracy of data is important in order to obtain accurate results. For this purpose, data on distances is taken from Iran's mapping agency and data on population and amount of generated waste in each district are taken from Tehran's waste management organization. Other required data have collected through digital libraries, conference papers and magazines, scientific

[4] (U.S. EPA Report, 2011)
[5] Global Warming Potential

books, official data bases, related theses and interviews with experts in Tehran's waste management organization. Then, the proposed model is solved and optimal location and allocation decisions have been determined. The results show that one of the potential locations for establishing landfill has been selected and of the potential locations for establishing incineration facilities six points with their energy recovery type have been selected and according to the terms governing the issue, the result seems acceptable for experts. Selected locations are shown in Fig. 3.

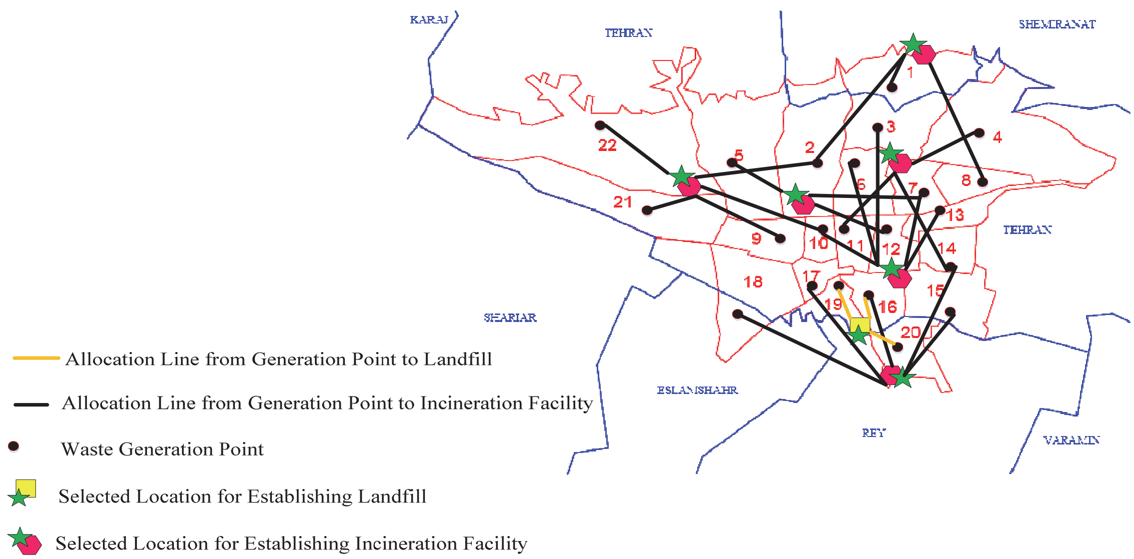

Fig. 3. Selected locations to establish landfill and incineration facilities in Tehran

Selected locations for incineration facilities and their energy recovery type $(Z_{kg} = 1)$ are mentioned in Table 2. It should be noted that in reality, the proceeds from the use of combined systems (heat and power) are more than other options further. Although heat recovery has the most efficiency, but since in the most cases power is sold more expensive than heat, use of combined systems will be more effective in terms of revenue.

Table 2
Selected locations to establish incineration facilities and their energy recovery type

Selected location for incineration facility $(Z_{kg} = 1)$	Energy recovery type 1 (CHP) $(g = 1)$	Energy recovery type 2 (Power) $(g = 2)$	Energy recovery type 3 (Heat) $(g = 3)$
$(k = 1)$	*	-	-
$(k = 4)$	*	-	-
$(k = 7)$	*	-	-
$(k = 8)$	*	-	-
$(k = 9)$	-	-	*
$(k = 10)$	-	-	*

Allocation of waste generation points to selected incineration facilities and landfill with the amount of waste transported in the collection network (X_{ik}) and (V_{ij}) can be seen in Table 3. The amount of ashes transported from selected incineration facilities to landfill in the collection network (W_{kj}) can be seen in Table 4. Total result of solving the model can be seen in Table 5.

Table 3
Allocation of waste generation points and the amount of waste transported in the collection network

Waste Generation Point (i)	Incineration facility1 $(k=1)$	Incineration facility4 $(k=4)$	Incineration facility7 $(k=7)$	Incineration facility8 $(k=8)$	Incineration facility9 $(k=9)$	Incineration facility10 $(k=10)$	Landfill 1 $(j=1)$
1	0	0	420	0	0	0	0
2	0	0	0	0	450	0	0
3	0	165.844	134.156	0	0	0	0
4	0	0	0	620	0	0	0
5	0	0	0	0	0	500	0
6	0	290	0	0	0	0	0
7	0	110	0	0	0	180	0
8	0	0	290	0	0	0	0
9	0	0	0	0	150	0	0
10	0	80	0	0	130	0	0
11	0	0	0	270	0	0	0
12	0	0	0	0	0	320	0
13	0	180	0	0	0	0	0
14	15.844	174.156	0	110	0	0	0
15	430	0	0	0	0	0	0
16	94.156	0	0	0	0	0	115.844
17	200	0	0	0	0	0	0
18	260	0	0	0	0	0	0
19	0	0	0	0	0	0	210
20	0	0	0	0	0	0	330
21	0	0	0	0	130	0	0
22	0	0	0	0	140	0	0
Sum	1000	1000	844.156	1000	1000	1000	655.844

Table 4
The amount of ash transported from selected incineration facilities to landfill

(W_{11})	(W_{41})	(W_{71})	(W_{81})	(W_{91})	(W_{101})
250.000	250.000	211.039	250.000	250.000	250.000

Comparison between present situation of Tehran's waste collection network and results from solving the model considering establishment of incineration facilities can be seen in Table 5.

Table 5
Comparison between present situation of Tehran's waste collection network and results of the model

Criteria of comparison	Present situation (without incinerators)	Model results (with incinerators)
Total demand	6500	6500
Active landfills	1	1
Active transfer stations	11	6
Direct transportation to landfill (tons)	1200	655.844
Transported amount from generation points to incineration facilities (tons)	5300	5844.156
Transported amount from incineration facilities to landfill (tons)	5300	1461.039
Total Transported amount to landfill (tons)	5300	2116.883
Landfill capacity (tons)	7500	2500
Unfulfilled capacity of landfill (tons)	1000 (13.3%)	83.117 (3.3%)
Total capacity of incineration facilities (tons)	7000	6000
Unfulfilled capacity of incineration facilities (tons)	1700 (24.2%)	155.844 (2.5%)
Average number of direct transportation to landfill	130	70
Average number of transportation from generation points to transfer stations	570	630
Average number of transportation from transfer station to landfill	285	40
Average number of total transportation to landfill	415	110

Therefore, applying incineration facilities in waste collection network has lots of advantages and helps the network improvement by increasing efficiency. Overall, from the managerial perspective, some of the most important pros and cons of applying incineration facilities is listed in Table 6.

Table 6
The most important pros and cons of using transfer stations equipped with incineration systems

Pros	• Saving a lot of money on transport of waste to landfills • Decrease in fuel consumption, the carbon footprint and fleet size • Reduction in needed land by decrease 90% in volume and 70% in weight • Possibility of neutralizing emission and their destructive effects • Decreasing the toxicity degree of wastes and disposal of dangerous waste • Elimination of gases and leachates that are produced in landfills by waste • Taking advantage of combusting process's remaining in various industries • No Methane producing during incineration process • Substituting fossil fuels with alternative energies • Preventing waste release and urban accidents during the routs • Reducing pollution, pests and insects at the transfer stations
Cons	• More investment cost compared to other disposal options • Existing concerns about incinerator's emissions on public opinion • The need to manage various solid output produced during the incineration • Making valuable recyclable dry waste out of the recycling cycle • Reducing the amount of public participation in waste separation/reduction by advertising done by the relevant authorities about the ability of incineration systems in elimination of significant amounts of waste • Need for skilled personnel and continuous maintenance

Now, in order to verify the behaviour of the model and the influence of changing various parameters on the results, sensitivity analysis has been performed on the sensitive parameters. Selected parameters for sensitivity analysis are weights of the first objective and capacity of landfill. As the weighting of the objective functions is executed according to the priorities of decision-makers, sensitivity analysis to changes in weights assigned to the objective functions can be addressed. Fig. 4 shows changes in the economic and social objective functions towards the first objective function's weight changes.

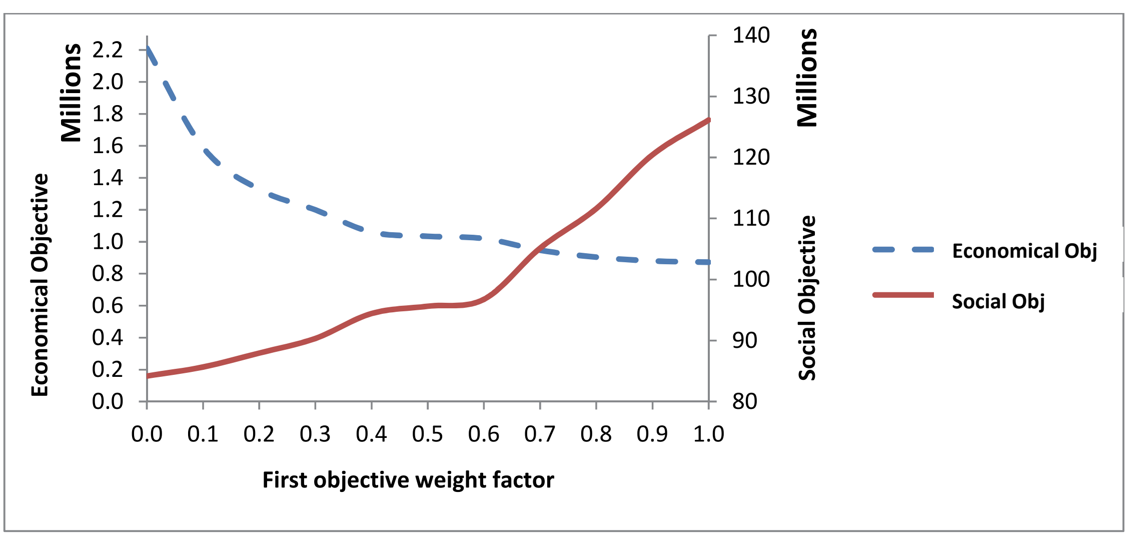

Fig. 4. Changes of objective functions towards changing first objective function's weight

As can be seen, per unit increase in weight of the first objective function, economical objective function shows too steep decline. This indicates that since the goals have conflict, with the increase of the first objective function's weight, minimizing this objective becomes more important and therefore economic objective function value decreases more. Similarly, with the increasing weight of the first objective function, the social objective function value increases since the focus is on minimizing the first objective.

For the case of changing the landfill's capacity, the results of the sensitivity analysis as in Fig. 5 show that both objective functions change and by increasing per unit of capacity their values decrease up to about 2100 tons for capacity and then the increases in capacity does not increase or decrease the value objective functions and they do not show sufficient sensitivity by changing capacity of landfills more than 2100 tons. High slope of the graph indicates that the model has shown high sensitivity of this parameter due to the impact of overhead costs to a certain extent.

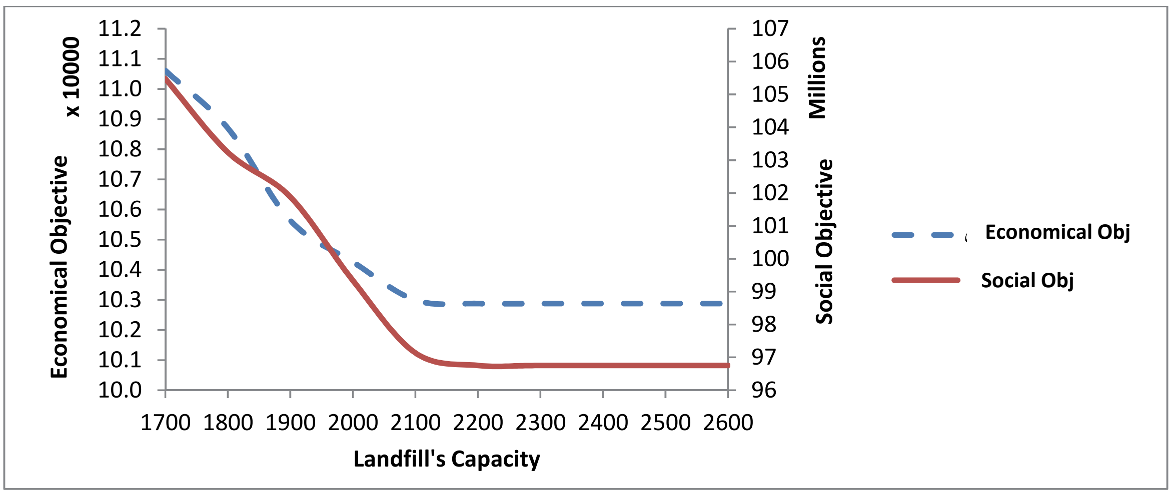

Fig. 5. Objective function behavior toward changing the landfill's capacity

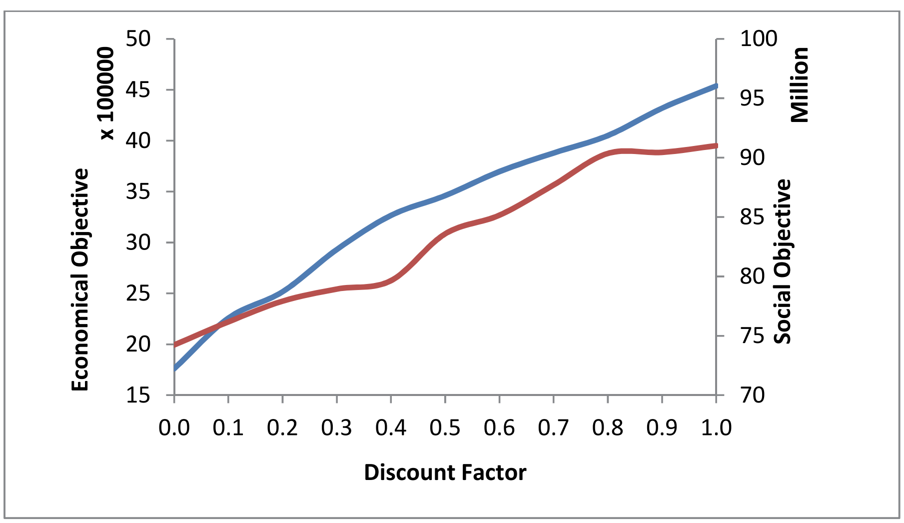

Fig. 6. Objective function behavior toward changing the discount factor

For the case of changing the discount factor, the results of the sensitivity analysis as in Fig. 6 show that both objective functions change and by increasing per unit of discount factor their values increase. The reason for the discount is justified by the fact that the transportation from customers involves smaller collection vehicles as opposed to the larger transport trucks that haul compacted waste from transfer stations to landfills. Clearly, the latter transport can be performed more cost-effectively, and this is what the discount factor captures. The results show that depending on the value of discount factor, the optimized solutions were between 10% and 40% less costly as compared to the present situation without incinerators.

8. Conclusion

One of the most important issues in waste management is minimizing service costs and reducing the environmental and social impacts. Finding an effective solution to decrease these adverse effects health is a worthy effort. In this regard, a new trend to move of many small landfill sites to a small number of large and remote landfills has been taken in recent years and the emergence of transfer stations in waste collection network has improved the performance of this network (U.S. EPA Report, 2000). Regarding the necessity of using alternative energy in recent years, the use of incineration facilities has increased throughout the world and has become an attractive option for municipal waste management.

In this study, Tehran's waste collection network has been addressed in order to determine location and allocation decisions for landfill and incineration facilities in the network. In this regard, ten potential locations for incineration facilities and three potential locations for landfill have been introduced. In the new approach of this paper to locate the facilities, minimizing costs and minimizing the visual pollution are considered, simultaneously. Also, environmental impacts of landfilling and incineration have been considered in model constraints.

Comprehensive waste management system consists of several options that should have proper and harmonious with each other. So, taking other decisions in this area with decisions on the facility location is required for a dynamic management of this system. In this regard, considering routing decisions seems inevitable requirements beside the facility location decisions. In addition, considering the routing decisions and the time windows for waste collection will have a large effect on reducing visual pollution. Using data of Tehran's waste management organization, numerical results show the number of active transfer stations and traffic reduce leading to waste collection network's efficiency increase. Moreover, not only significantly the need for landfilling and amount of hazardous methane emissions decrease but also power and heat as alternative energies are recovered.

Considering incineration facility location problem with the reliability to deal with unforeseen events, natural and human risks resulting to failure or even periodic repairs is another future research field which is vital in waste management. Also, considering the uncertainty in the model parameters is very important and further researches should focus on presenting a robust optimization approach to confronting the existing uncertainty. Finally, using metaheuristic approaches for development of the proposed model in future studies is suggested.

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