Resources, Conservation and Recycling 60 (2012) 89–98

Contents lists available at SciVerse ScienceDirect

Resources, Conservation and Recycling

journal homepage: www.elsevier.com/locate/resconrec

A methodology to optimally site and design municipal solid waste transfer stations using binary programming

Constantinos Chatzouridis, Dimitrios Komilis*

Laboratory of Solid and Hazardous Waste Management, Dept. of Environmental Engineering, Democritus University of Thrace, Xanthi 671 00, Greece

ARTICLE INFO

Article history:
Received 19 July 2011
Received in revised form
11 December 2011
Accepted 12 December 2011

Keywords:
Binary programming
Collection
Municipal solid wastes
Mathematical optimization
Waste transfer stations
Cost minimization

ABSTRACT

Mathematical programming has been often used to optimize municipal solid waste management and transfer systems. The objective of this work was to develop a practical methodology to aid in the optimal design of a solid waste collection network in regions with well-specified boundaries. The objective function was a non-linear equation that minimized total collection cost. The cost comprised the capital and operating costs of: (i) the waste transfer stations, (ii) the waste collection vehicles, (iii) the semitrailers and tractors as well as the waste collection within a community, and the cost to haul the wastes to the transfer stations or to the landfills. The adjustable (decision) variables were binary variables that designated whether a path between two nodes is valid or not. Binary variables were also used to designate whether a transfer station should be constructed or not. In this methodology, the waste production nodes and their waste production rates were specified. The locations of all candidate waste transfer stations were designated using two alternative GIS-based siting methodologies; the locations of the final nodes (landfills) were precisely specified too. The actual travel distances and times among all nodes were the main input variables. The model was developed in an Excel® spreadsheet and was applied to a Hellenic region that has 53 municipalities. The candidate transfer stations sited in the region were 47 and one or two landfills were present in the system. The optimal solution suggested that 47 and 6 municipalities should direct their wastes to 12 transfer stations and to 2 landfills, respectively. The 12 transfer stations should then transfer their wastes to their adjacent landfills. The optimal collection cost was €42.4 t^{-1}. A sensitivity analysis concluded that fuel cost was the most sensitive parameter in the model.

1. Introduction

Linear and non-linear mathematical programming has been often used to optimize municipal solid waste (MSW) managements systems (Badran and El-Haggar, 2006; Göttinger, 1986). It has been also used to optimize the haul and transfer of municipal solid wastes (Arribas et al., 2010; Bonomo et al., in press; Chang et al., 1997; Karadimas et al., 2007; Kim et al., 2006; Komilis, 2008; Kulcar, 1996; Male and Liebman, 1978; Or and Curi, 1993). Geographical Information Systems (GIS) software has been frequently applied to aid in solid waste routing problems within communities (Ghose et al., 2006; Kanchababhan et al., 2011; Karadimas and Loumos, 2008). Limited work appears to exist, however, on methodologies to optimally design and allocate waste transfer stations, when the only available data are the locations of the initial nodes (municipalities) and of the final nodes (landfills).

The basic element in any MSW collection model is to define the location of all nodes (initial, intermediate and final) that are present in the MSW haul network (Clark and Lee, 1976). Provided that the nodes are clearly designated, all possible paths among all nodes should be clearly defined and included in the model as the main input variables (Badran and El-Haggar, 2006; Komilis, 2008; Or and Curi, 1993). The initial nodes are usually the waste production (or generation) nodes (WPN), such as municipalities, cities or villages. The intermediate nodes are the waste transfer stations (WTS), while the final nodes are the landfills and/or any waste treatment facilities that are likely present in the system. MSW produced by the WPN are collected and transferred directly either to the WTS, or to the landfills, via typical waste collection vehicles (WCV). MSW that are hauled to the WTS are, then, transferred to the final nodes (landfills) via tractor hauled semitrailers (or containers) that have a 4–5 times greater waste capacity than the WCV.

The construction and operation of WTS in a MSW collection network becomes beneficial when the distance between a WPN and a landfill exceeds a certain threshold value. This threshold distance depends on the economics of WTS and the unit haul costs to transfer MSW via the WCV or the semitrailers (Komilis, 2008). These unit waste haul costs are commonly expressed in cost units (e.g., € or $) trip t^{-1} km^{-1} and vary between smaller vehicles, such as the WCV, and larger vehicles, such as the tractor hauled

* Corresponding author. Tel.: +30 25410 79391; fax: +30 25410 79391.
E-mail address: dkomilis@env.duth.gr (D. Komilis).

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doi:10.1016/j.resconrec.2011.12.004

semitrailers. That is, the smaller the vehicle, the higher the unit haul cost becomes. According to Komilis (2008), WTS in Greece become financially beneficial when the one-way distance between a WPN and a landfill is greater than 65 km. According to USEPA (2001), the threshold (or break-even) one-way distance between a city and a landfill that can make a transfer station economically viable ranges from 24 to 32 km. Therefore, optimum distances to site WTS are highly site specific, and depend on local and country economics.

The objective of this work was to develop a practical methodology to aid in the optimal design and siting of MSW transfer stations (WTS) using a combination of GIS and binary programming (BP). The methodology was applied to a Hellenic Region. The mathematical optimization model was developed in a simple spreadsheet (Excel®) to allow a user-friendly environment. A commercially available optimization software (Extended version of What's Best 7.0® by Lindo Systems Inc.®), that operates as an add-in to Microsoft's Excel®, was used. The novelty of this methodology is that can be applied to situations where neither the number, nor the locations of the WTS are previously designated. On the other hand, the number and locations of the WPN and the final nodes are necessary input data. The outputs of this methodology are the precise locations of the required WTS, the design capacities (in $t\,d^{-1}$) of the WTS and the optimal pathway to haul MSW from the WPN to the WTS and then to the landfills.

2. Methodology

The proposed methodology consists of four parts, which are:

(i) To exclude the areas unsuitable for WTS siting.
(ii) To site all candidate waste transfer stations in the remaining suitable areas using a siting approach.
(iii) To develop an objective function (OBF) that minimizes total solid waste collection cost.
(iv) To develop the model in a user friendly environment, such as an Excel® spreadsheet.

2.1. Exclusion of unsuitable areas

The common environmental impacts of waste transfer stations are noise, dust, odors, litter and traffic congestion (USEPA, 2001). For these reasons, waste transfer stations can be considered as point sources of pollution and could be sited using siting criteria similar to that for landfills. For example, WTS cannot be located close to residences, water bodies or the coast line. Environmentally sensitive areas (e.g., natural habitats) and areas with slopes higher than a specified gradient should be also considered unsuitable for WTS siting. On the other hand, it is preferable to locate WTS near an existing road network. GIS software can be used to develop thematic suitability maps.

Table 1 summarizes the WTS exclusion criteria that were used in this work. The criteria were partially based on landfill suitability criteria mentioned in Kontos et al. (2003) as well as on rough guidelines mentioned in USEPA (2001).

Table 1
Exclusion criteria as applies to waste transfer station siting in urban and suburban areas.[a]

Criteria	Total site exclusion	Exclusion buffer zone
Urban centers	Yes	1000 m
Villages	Yes	500 m
Rivers	Yes	500 m
Lakes	Yes	500 m
Swamps	Yes	500 m
Coast lines	–	500 m
Natural habitats according to Natura 2000	Yes	–
Land use	All sites excluded except areas of low agricultural activity.	–
Land morphology	Gradients > 10%	–

[a] Partly based on Kontos et al. (2003) and USEPA (2001).

2.2. Siting approaches

The previous step provides all areas unsuitable for WTS siting; therefore, all remaining areas are suitable to site a WTS. According to USEPA (2001), the distance between a WPN and a landfill is, commonly, the most critical parameter when siting WTS.

Two siting approaches were used in this work, which were to:

(a) Site transfer stations close to municipality centers (approach A).
(b) Site transfer stations in critical locations so that to serve multiple municipalities (approach B).

The former approach (A) considered that candidate transfer stations should be located as near as possible to a municipality center and close to an existing major road network. Based on approach B, the candidate transfer stations were located within a distance of 16 km (10 miles) from the waste production nodes. According to USEPA (2001), "*transfer stations should be located no more than 16 km from the end of all collection routes in urban and suburban areas*". In order to do that, 16-km radius buffer zones were drawn around the centers of all waste production nodes; the candidate WTS were then sited at the center of the intersections of these buffer zones. As an example, Fig. 1 shows the intersection of the three 16-km radius buffer zones of three adjacent municipalities. The darkest area is the most preferred area to site a WTS under siting approach B, since it can simultaneously serve 3 WPN.

According to approach A, WTS were sited at distances that varied from 1 km to 5 km from the centre of a municipality. In most cases, candidate WTS were located in distances between 1.5 and 2 km from a WPN center. Based on approach B, transfer stations were sited in the centers of the intersections of the 16-km radius buffer zones, as previously mentioned. When more than 2 buffer zones intersected, then a WTS was placed in the center of the intersection that resulted from the highest number of buffer zones.

2.3. Optimization model

The 3rd step of the methodology was to develop the optimization model. An optimization model comprises an objective function, the decision (or adjustable) variables and the constraints. In order to do that, all available travel distances (km) and travel times (h) among WPN, WTS and the landfills should be precisely calculated. These are the main input data that are included in the optimization equation.

2.3.1. Objective function

The objective function (OBF) that was developed here is similar in principle to the OBFs suggested by Or and Curi (1993), Badran and El-Haggar (2006) and Komilis (2008). The OBF minimizes total collection cost which consists of the fixed (capital) cost (CC) and the operating cost (OC). The CC in this work is comprised of the capital cost of the waste collection vehicles (WCV), the tractors and containers (Tr), and of the capital cost to construct a WTS. The operating