Computers & Operations Research 62 (2015) 305–315

Contents lists available at ScienceDirect

Computers & Operations Research

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

Location modeling for municipal solid waste facilities

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ARTICLE INFO

Available online 17 May 2014

Keywords:
Municipal solid waste
Landfill siting
Solution approaches
Mathematical formulation
Decision analysis

ABSTRACT

This paper introduces the landfill siting problem by way of (usually ill-fated) examples. It then discusses different classes of decision-making models and formulates a generic cost-minimization model for that purpose. It continues to describe some multi-criteria decision models that have been used for landfill siting. The paper then surveys landfill location models that have appeared in the literature during the last forty years. The work concludes with a framework that "zooms in" and uses existing techniques to determine sites for solid waste facilities.

1. Introduction

It is not often that garbage makes the news. Notable exceptions are the case of the itinerant barge, which set sail in 1987 from Islip, Long Island, New York to North Carolina, where its cargo was to be used in a waste-to-energy facility. Due to concerns regarding the shipment, it was refused in North Carolina, from where it went on to Louisiana, Mississippi, Texas, and Florida, but all ports refused. Mexico and Belize refused as well, so that the barge returned to New York. After a judge ruled that the garbage should be dealt with where it was generated, it was finally, after 6 months, incinerated in Brooklyn (for details, see [86]). And then there was the case when in 2001 Toronto City Council in Ontario, Canada, voted down the proposed new landfill at the Adams Mine, after a 10-year search that involved elaborate political wrangling. A timeline of the case is provided in [35]. Or the notorious case of tires in Ontario that the government of the day did not want to deal with unless a perfect solution were to exist.

Central Arizona Project [17] defines municipal solid waste (MSW) as "Waste generated in households, commercial establishments, institutions, and businesses. MSW includes used paper, discarded cans and bottles, food scraps, yard trimmings, and other items. Industrial process wastes, agricultural wastes, mining waste, and sewage sludges are not MSW." In the remainder of this paper, we will use the terms "*MSW*," "waste," "trash," and "garbage" as synonyms. Typically (see, e.g., [47]) we distinguish between four phases of waste management: generation, collection, treatment, and disposal. The main topic of this paper concerns the locations of facilities, thus impacting the collection phase (due to different facility-customer distances), the treatment phase (in case the model includes different treatment options), and the disposal phase (as sites for final disposal are located). Here, we will concentrate on transfer stations and landfills, even though similar models would apply to other treatment facilities as well. For a model that chooses the treatment option, see Khan and Faisal [62].

Garbage generation has steadily increased over time. For instance, in 1960 the total amount of waste generated in the United States was 88.1 million tons, which increased to about 250 million tons in 2008. This corresponds to a per-capita generation rate of 2.68 lbs (1.22 kg) in 1960, and 4.5 lbs (2.04 kg) in 2008 [38]. To provide an international perspective, countries, such as Canada, France, and Japan, have daily generation rates of 3.86 lbs (1.75 kg), 3.26 lbs (1.48 kg), and 2.47 lbs (1.12 kg), respectively [83], Turkey produces 2–2½ lbs (0.9–1.14 kg) per capita per day [103], while Southern India reports garbage generation of 1 lb (0.5 kg) per capita per day (Sumati et al., 2008) and Chinese citizens produce an average of about ⅔lb (0.3 kg) per capita and day [51]. It is important to note that garbage composition differs significantly between countries. Typically, more developed countries have a significantly higher content of paper and packaging products, while waste in less developed countries contains more organic matter, see, e.g., Wilson et al. [110].

The actual composition of garbage will, of course, determine how it can be processed: organic matter lends itself more to composting, paper-based products may be recycled or used in waste-to-energy facilities, and so forth. Recycling has increased steadily and significantly during the last half century. In 1960 in the United States, only about 6.4% of the generated waste was recycled. This contrasts sharply with the 34.1% in 2010, while another remaining 11.7% being incinerated with energy recovery, and 54.2% are discarded, i.e., landfilled [38]. Recycling in other developed countries is at similarly high levels: Switzerland recycles more

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http://dx.doi.org/10.1016/j.cor.2014.05.003
0305-0548/

than half of its waste, Germany recycles 48%, and Sweden recycles 34% of the municipal solid waste [4]. Furthermore, as of 2005, German landfills accept only preprocessed garbage, especially with respect to organic waste. As of 2020, there should be no more landfills (see [14]). However, country averages only tell part of the story. For instance, while San Francisco recycles about 69% of its waste, Houston recycles only 2.6% [34].

Given the increasing demands for environmental protection, small neighborhood dumps became a liability and their use was no longer feasible. However, well-constructed and properly lined sanitary landfills are expensive, and they are only viable given a certain size. The pertinent statistics are clear: while there were close to 8000 landfills in the lower 48 of the United States in 1988, their number had decreased to 1908 in 2010, see van Haaren et al. [104]. This does, of course, mean longer transportation routes. Rather than using the smaller and—for that purpose—less efficient collection vehicles, transfer stations are used, in which the garbage is unloaded by the collection vehicles, possibly compacted, and then loaded onto more efficient trailers that haul the garbage to the landfill. The EPA [37] and Antunes [5] estimate that transportation costs on transportation trailers are only about 30% of the costs incurred by the same quantity hauled by the collection vehicles.

When modeling, it is important to distinguish between municipal solid waste and hazmat. While the basic ideas are similar, risk is a criterion that is of utmost importance in dealing with hazardous materials, while it is a minor issue in the processing of household waste (except for the consideration of leachate, which is typically dealt with in a selection phase that excludes unsuitable sites), while hazmat models usually include risk in a separate objective function. There are, however, a few examples in which municipal solid waste has created hazardous situations, such as the 1993 explosion of the Istanbul landfill due to landfill gases [76].

2. The main issues and major approaches

As any model will depend on (1) the issue it deals with, (2) the individuals who are using it, and (3) those affected by it, it is useful to first identify the "players" involved. Following Kleindorfer and Kunreuther [63], we can identify

- the applicant,
- those affected by the facility,
- public interest groups, and
- regulatory bodies.

The applicant may be a municipality, a county, or a state, or a private contractor operating for the local or regional government. The affected constituents are the people whose trash is picked up (the positive effect), and those who live sufficiently close to the facility or one of its access routes and who suffer the dirt, noise, or other pollution as well as deteriorating property values (the undesirable effects). Public interest groups include political parties or groups that lobby for a specific purpose on behalf of others. In this context we refer to those groups that have not been asked by the directly affected constituents to speak on their behalf. Finally, regulatory bodies involved are those that grant permits and licenses. A larger list of actors or players for civil engineering projects is put together by Tavares [100]. It includes "beneficiaries," (whose needs are addressed by the system) "users," "pressure groups," "promoters," "owners," "project managers," "builders," "financial operators," "licensing authorities," and "controllers & certifiers."

The main concerns of the municipality will be to provide service, and to do so as cost-effectively as possible. The beneficiaries or constituents want to minimize the costs, but also want to ensure that some environmental concerns are addressed, including the purity of their water, and a limitation of pollution that manifests itself most prominently in the form of dust and noise. Also, maintaining their property values is an important concern. Concerns of the lobbying groups are best described by any of the many acronyms that have been created in this context, among them *NIMBY* (not in my back yard), *NIMTO* (not in my term of office), *LULU* (locally unacceptable land use), *BANANA* (build absolutely nothing anywhere near anything), and others. Finally, regulatory bodies have the duty to enforce regulations, some of which are listed below.

Regarding specific concerns in the location process, Erkut and Moran [36] distinguish between the major classes "environmental factors" (including geology topography, and ecology), social factors (including social acceptability, traffic, land use and ownership issues, and property values) and economic factors. The following list outlines some details of these concerns.

- Access to transportation (i.e., proximity to existing highways)
- Existing services (including electric power, water, and sewage)
- Existing suitable land (typically at least 100 acres for a landfill and 40 acres for a transfer station)
- Geology in the area (preferably clay substrata, not situated in an earthquake-prone area)
- The slope of the area
- Surface water (proximity to lakes and rivers, wetlands, 100-year flood plains)
- Ground water (location of the main aquifers)
- Air quality (downwind given prevailing wind direction)
- Proximity to urban centers (in order to minimize transportation distances)
- Proximity to public and private places (avoiding pollution to houses, hospitals, parks, official buildings, and airports)
- Land claims
- Detrimental effects on agricultural land and fisheries, and
- Property values

An extensive list of factors involved in the process is provided by Vasiloglou [105] and Latonas and Kucera [69]. The factors listed above cannot be uniquely assigned to one of the four stakeholders. For instance, while property values are of primary interest to those directly affected by a facility, the municipality will suffer an (albeit minor) effect of diminishing tax base due to lower house evaluations. Much more obvious are the location and operating costs of the facility, which, while directly paid for by the municipality or region, will eventually be paid for by the people who benefit (and, in part suffer the effects of pollution). Such an "aligning of objectives" reduces the degree of confrontation and facilitates optimization.

An important question is which factors are put into the constraints and which ones are formulated as objectives. As in any optimization, we use the concept that what *must* be satisfied will be written as a constraint, while the factors that *should* be achieved or satisfied, will be written as an objective. Using this concept, regulatory issues such as minimum required distances to buildings, or proximity to sources of water are clearly constraints, while issues such as property values or proximity to existing highways are clearly cost issues that will typically find their way into the objective function (or one of the objectives, in case of multiple objectives).

Those factors that are used as constraints are typically dealt with by means of geographical information systems (*GIS*). The overlays allow decision makers to visualize areas that satisfy all constraints. It also permits to picture the effects of strengthening or weakening some rules, such as modifying the minimal required distances between a proposed site and existing natural or man-made features.