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Decision Support

A bi-objective model for the location of landfills for municipal solid waste

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ABSTRACT

This paper models the locations of landfills and transfer stations and simultaneously determines the sizes of the landfills that are to be established. The model is formulated as a bi-objective mixed integer optimization problem, in which one objective is the usual cost-minimization, while the other minimizes pollution. As a matter of fact, pollution is dealt with a two-pronged approach: on the one hand, the model includes constraints that enforce legislated limits on pollution, while one of the objective functions attempts to minimize pollution effects, even though solutions may formally satisfy the letter of the law. The model is formulated and solved for the data of a region in Chile. Computational results for a variety of parameter choices are provided. These results are expected to aid decision makers in the choice of excluding and choosing sites for solid waste facilities.

1. Introduction

For a long time, locations of facilities have been discussed by geographers, mathematicians, computer scientists, economists, and, last, but not least, operations researchers. However, it was only in the 1970s that researchers formally realized that not all facilities are desirable and customers find it beneficial to be close to them. In particular, the contribution of Church and Garfinkel (1978) was the introduction of the concept of "obnoxious" facilities. Later discussions realized that most facilities are neither entirely desirable nor entirely undesirable: a nearby supermarket is certainly beneficial to the people living in its proximity, but those very close by will not be too pleased by the early morning deliveries that are inevitably accompanied by noise and other sorts of pollution.

Similarly, not all polluting facilities are the same. Early contributions to the field distinguished between noxious and obnoxious facilities, even though the distinction was purely semantic and was not reflected in the model. Erkut and Neuman (1989) suggested instead the more general term "undesirable facilities," which has been more or less universally accepted today. However, such unification of models may not necessarily be warranted. As an example, consider a nuclear power plant and a truck reloading station. Both are arguable undesirable facilities (in the sense that most people would not want to have them very close to their home), but they differ to a large degree by the actual risk they pose. While the nuclear power plant poses a tiny, but disastrous risk, the transfer station does not. From a modeling point of view, a mathematical model that locates a truck reloading station will have to address pollution, whereas it is typically not required to consider risk, which would not only be minimal, but also marginal. On the other hand, ignoring risk in a model that locates nuclear power plants would be foolish.

Landfills that accept municipal solid waste, the subject of this investigation, are facilities that pose some environmental risks. Other than freak accidents such as the explosion of the Istanbul landfill in 1993 that claimed 39 lives, (Harriyet Daily News, 2012), risk is mostly due to pollution of ground and surface water, and, to a lesser degree, air and noise pollution. These issues are typically taken care of in constraints that simply do not allow the location of landfills in areas that do not have appropriate soil types (compacted clay with low hydraulic conductivity) or are in 100-year flood plains, and those that specify smallest acceptable distances between landfills and populated areas. Similarly, if a potential location does not have appropriate access to the existing highway system, does not have desirable topographical features (e.g., the terrain is too steep), or does not have required soil properties, overlays in GIS systems can be used to simply not consider any such location.

However, residents today are no longer happy with enduring industrial or commercial facilities, even if they are not in direct vicinity of their property. They will complain about health hazards, environmental pollution, noise, truck traffic, and decrease

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in property values. The *NIMBY* (*n*ot *i*n *m*y *b*ack *y*ard), *NIMTO* (*n*ot *i*n *m*y *t*erm of *o*ffice), *LULU* (*l*ocally *u*ndesirable *l*and *u*se), and *BANANA* (*b*uild *a*bsolutely *n*othing *a*nywhere *n*ear *a*nything) and other, similar, syndromes are a clear testament to that sentiment. The model presented in this paper will add one more item to the alphabet soup: the *L-SOUP*, i.e., the *l*ocation of *so*cially *u*ndesirable *p*remises.

The duality of regulations and general sentiment in the population has caused us to use an approach that deals with pollution on two levels. The "hard" side of pollution will be dealt with by means of constraints, while the "soft" side is put into an objective function. For a discussion of soft and hard requirements, see e.g., Eiselt and Laporte (1987). The constraints will reflect what laws, bylaws, and other regulations prescribe in terms of maximal allowable pollution levels. In addition to that, the objective function that deals with pollution will attempt to minimize the detrimental effects generated by landfills and transfer stations.

Even though most people would consider a landfill a necessary, but undesirable facility, it is rarely treated as such from a formal point of view. As Eiselt and Marianov (2012) demonstrate, early contributions mostly use cost minimization to arrive at optimal landfill locations (Marks & Liebman, 1971; Fuertes, Hudson, & Marks, 1974; Gottinger, 1988 and others). The idea behind this is that while landfills are inherently undesirable to neighbors close by, the undesirable effects diminish fairly rapidly with distance. On the other hand, since the costs of collection, treatment, and disposal are eventually borne by the population at large, their interest is to have the treatment and disposal sites not too close, but sufficiently close to be reasonably cost-efficient, making it a model with a "pull" objective (see Eiselt & Laporte, 1995, for different classes of objectives) and "forbidden areas", i.e., a areas near the population center, in which it is prohibited to locate a facility. An interesting contribution that does take the populations sentiment directly into account is by Fernández, Fernández, and Pelegrín (2000), who locate a single facility in such a way as to minimize population opposition, which is modeled by a sigmoid repulsion function.

Most models that site solid waste facilities have a few features in common. They feature population centers at known and fixed locations with fixed and known numbers of people living there, a finite or infinite number of potential locations at which landfills and/or transfer stations can be located, and distances between them. As far as the choice of metric is concerned, many network models use shortest distances between customers and facilities, while models in the plane use Euclidean or some other Minkowski distance. In reality, we will have to distinguish between the distance between points when it comes to transportation (for which road distances are relevant), and the straight line or Euclidean distances representing how the pollution more likely moves. In order to avoid having multiple distance measures in the same model, many authors use Euclidean distances for both, transportation and pollution. This is not only an approximation for transportation, but it also approximates pollution, as the propagation of pollutants depends on the medium: models that involve air pollution typically use Gaussian plumes, while pollution in ground water follows the aquifer (see, e.g., Daly & Zannetti, 2007, chap. 2 for air pollution, and Persson & Destouni, 2009, or Stuart, Lapworth, Crane, & Hart, 2012 for groundwater pollution).

The last two decades have seen many new models and approaches. However, a common theme is to use mathematical (cost-) optimization to find approximate locations of the proposed landfill, and then employ tools from the toolkit of multicriteria decision making to incorporate different and, at least partially, contradicting criteria. Examples for such approaches are Lahdelma, Salminen, and Hokkanen (2002), Kontos, Komilis, and Halvadakis (2003), Sumathi, Natesan, and Sarkar (2008), and Xi et al. (2010).

From a macro point of view, the number of landfills has decreased dramatically throughout the last decades. For instances, while there were close to 8000 landfills and dumps in the United States in 1988, there were only 1908 in 2010 (van Haaren, Themelis, & Goldstein, 2010). This means that existing and new landfills will have larger capacities (thus increasing the level of undesirability) and many population centers will no longer have a landfill in their direct vicinity, thus necessitating long transportation routes. In order to mitigate the latter effects, waste transfer stations have been established, to which garbage is hauled in collection vehicles, where the waste is compacted and reloaded onto larger and more efficient transfer truck, which haul the waste to the treatment facility or the landfill. This means that landfills and treatment centers on the one hand, and transfer stations on the other, have to be included in one comprehensive model, as the location of one such facility will influence the location of the other.

There are very few contributions that plan the location and the size of a landfill in one comprehensive model. One of the difficulties of such a plan is that the model tends to become not only integer, but also nonlinear, thus tremendously increasing the degree of difficulty. To see this, suppose that Q_j denotes the size of a landfill at potential site j, and y_j is a binary variable that indicates whether or not a landfill is going to be constructed at site j, both Q_j and y_j are variables. The capacity of the landfill at site j is then Q_jy_j, a nonlinear expression. One possibility is to use only a finite number of potential landfill sizes, i.e., discretize the landfill size. Although it increases the size of the model, this is the approach we are using.

One of the few contributions that simultaneously optimize location and capacity is by André, Velasco, and González-Abril (2009). That paper locates a sequence of facilities on a plane, one at a time, over a time horizon, avoiding forbidden regions around population nodes, and precluding location of a new landfill within a preset distance of a closing landfill.

Our contribution is a linear integer model that addresses the location and sizing of landfills and, simultaneously, locates transfer stations. We minimize costs and pollution, the latter emanating from all facilities that are located and measured at all populated centers. The model considers economies of scale, i.e., larger landfills are less expensive per unit of received waste. By using discrete sizes, we can deal with economies of scale in a linear model. We also consider a policy consisting of defining *saturation zones* (or *exclusion zones*) around each facility, so that a populated point cannot fall in more than one such exclusion zone. The idea is that a customer, being relatively close to a polluting facility, is "saturated with pollution", and cannot be subjected to additional pollution from any facility that belongs to the system that handles municipal solid waste. While the size of an exclusion zone for a landfill depends on the landfill's capacity (assuming that a larger landfill will have more traffic and thus more pollution), the exclusion zone around a transfer station is assumed to be constant. Finally, since a common policy is to limit the allowable pollution imposed on any populated center, we add a constraint that establishes upper bounds on pollution at every such populated center.

The remainder of this paper is organized as follows. Section 2 presents our model, which includes the location of landfills and transfer stations, as well as capacities of landfills. Section 3 introduces the region of study and delineates our computational results with a variety of sensitivity analyses. Section 4 summarizes our findings and provides some thoughts regarding future research.

2. The model

Consider a region, in which population centers are located at known sites $i = 1, \ldots, m$. Typically, population is aggregated at these centers, so as to keep the size of the model manageable. We assume w_i customers are located at site i, each one generating γ tons of garbage per year, so that we have to deal with γw_i tons of