Location Analysis Helps Manage Solid Waste in Central Portugal

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By the beginning of the 1990s, the Portuguese Centro Region was suffering from extremely serious solid-waste-sector problems. The Portuguese Centro Region Coordination Agency asked me to prepare a document identifying the main issues involved in finding a solution to the existing problems and to propose a master plan for intervention. My proposal defined a network of sanitary landfills and transfer stations covering the whole region (23,700 square km; 1,714,000 inhabitants). The proposal was the basis for the discussions held at the regional council and for the solution that is currently being implemented. To define the network, I developed a mixed-integer optimization model combining elements of a p-median model and a capacitated-facility-location model with transshipments.

From 1974 to 1993, the Centro Region of Portugal (Figure 1), like the rest of the country, experienced extensive political, economic, and social change. Major increases in urban activity and urban population accompanied this change.

In 1970, Portugal was still very much a rural society. At that time, more than 30 percent of the working population was employed in the agricultural sector, and the only two cities with more than 100,000 inhabitants, Lisbon and Oporto, generated significant amounts of municipal solid waste (MSW). But even in those cities, the quantities of MSW produced were far less than the quantities associated with the cit-

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GOVERNMENT—SERVICES
FACILITIES PLANNING—LOCATION—DISCRETE

Figure 1: The Centro Region occupies 23,700 square km of land, is located between the Atlantic Ocean and the Spanish border, and is divided into 78 municipalities. The 1991 census reported the region's total population at 1,714,000 inhabitants, who were evenly scattered across the area. The population of the largest municipality, consisting of the city of Coimbra and surrounding areas, was only 140,000 inhabitants.

ies of developed countries.

Two decades later in 1991, the year of the latest census, the percentage of workers in the agricultural sector had decreased to 10 percent, and generation of MSW could, on the basis of available data (rather inaccurate), be described as follows:

(1) Average per capita MSW ranged from 0.80 kg per day in large municipalities (more than 60,000 inhabitants) to 0.65 kg per day in intermediate municipalities (between 30,000 and 60,000 inhabitants) and to 0.50 kg per day in small municipalities (Figure 2).

(2) Growth rates equaled 1.75 percent per year, on average, in large, intermediate, and small municipalities.

During the '80s, authorities at the central and the local level began to realize that there was a solid waste problem, and by the beginning of the '90s, it was clear that this problem was serious almost everywhere in the country.

Initially the authorities' efforts were mainly devoted to creating modern fleets to collect MSW. In 1991, 90 percent of households were already covered by collection services. Several municipalities were collecting glass, paper, and other recyclables separately.

Municipalities paid much less attention to MSW disposal. Typically, they disposed of MSW at open-air dumps, which burned the waste from time to time. This is widely recognized to be the worst possible disposal technique.

Many municipalities were apparently conscious that they needed another kind of solution as indicated by local initiatives, which were often guided by sellers of MSW equipment. These initiatives usually required financial means far beyond municipality capacities.

The municipalities soon understood that they would never be able to gather those means and turned to the government, more precisely to the regional coordination agencies, for assistance.

Those agencies, which administer government money to promote regional development, were then faced with a complicated situation. They were put under pressure to solve the disposal problem by the municipalities, the media, and environmentalists, without having a clear, global view of what to do and when to do it.

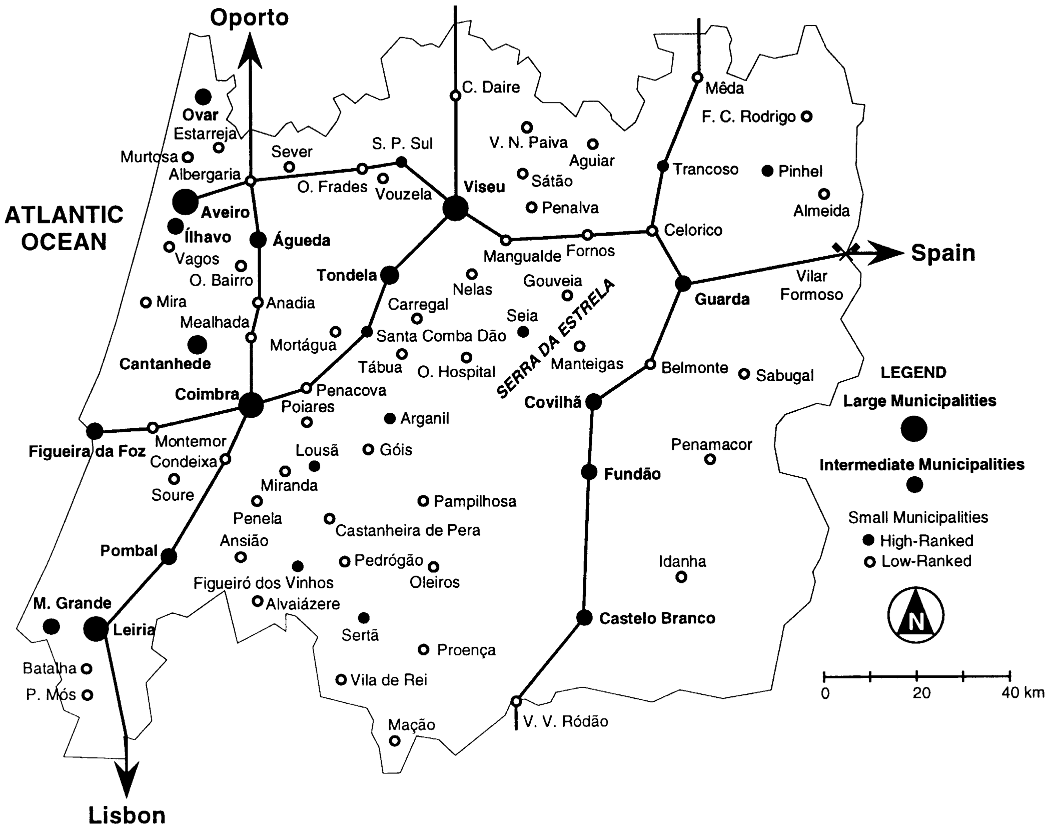

Figure 2: The largest centers of the Centro Region are located along the main Portuguese roads, IP1 (Lisbon-Oporto) and IP5 (Aveiro-Vilar Formoso). The latter passes north of Serra da Estrela, the Portugal's highest mountain (2,000 m), an outstanding natural park that should not be crossed by MSW collection vehicles and transfer trucks. Small municipalities classified as highly ranked were selected by the administration to receive important beneficial public facilities.

I performed a study for the Centro Region Coordination Agency (CCRC) with the explicit purpose of clarifying the decision-making context for the many parties involved and producing a well-supported solution to the existing MSW problems. This solution would serve as a starting point for future negotiations. I did not address problems raised by hazardous, dangerous solid waste like that generated by hospitals, for which the government was already working out a separate, specific solution.

Management Process

In formulating a solution to MSW management in a given area, it is crucial to have a clear view of the management process, that is, the sequence of stages occurring between the moment waste is generated and the moment it is disposed of, preferably in a sanitary landfill.

Several good textbooks deal with this subject (for instance, Pfeffer [1992] and Tchobanoglous, Theisen, and Vigil [1993]), as well as some useful guides for decision makers prepared by specialized organizations (for instance, US EPA [1989] and ADEME [1993]).

The main ideas contained in these references may be synthesized as follows:

(1) The management process includes four basic stages: generation, collection, reduction, and disposal.

(2) The most efficient actions to reduce waste quantity and separate waste components (for subsequent recovery and recycling operations) are taken in the generation stage; however, after that, there will always be a considerable amount of waste to collect and to dispose of.

(3) The management process will not be adequate unless the final destination of waste is a sanitary landfill, built and operated according to the applicable rules.

(4) Between the collection and the disposal stages, some MSW processing operations, such as separation, composting, compaction (or densification), and incineration, may be employed to reduce the space needed to store waste.

(5) To reduce storage space, incineration and compaction are the most effective operations, reducing waste to, respectively, 10 and 25 percent of the initial volume. Composting is much less effective, applying only to the organic portion, which in the Centro Region amounts to less than 40 percent of total waste, and this percentage tends to decrease over time. Separation is intended mainly to retrieve the metallic portion of MSW, and it is normally used only with incineration or composting. Once MSW is collected, it is too late to separate glass, paper, cardboard, plastic, and textiles, because of the contact contamination that arises during collection.

(6) Although it is the most effective way of reducing waste volume, incineration is not an attractive solution from an economic standpoint if widely accepted principles of environmental safety are to be observed, except perhaps under conditions of severe shortage of space. Setup costs of incinerators are very high compared to those of sanitary landfills, and the difference is not compensated by smaller operations costs (even after deducting the possible benefits arising from steam and energy production, and before adding the costs for eliminating the hazardous materials it generates, such as bottom and fly ashes).

(7) Compaction is not as effective as incineration, but it has the advantage of requiring relatively inexpensive equipment. It becomes especially interesting when it is accomplished close to generation sources, because this decreases transport costs to about 30 percent of the costs of transporting uncompacted MSW. Municipalities can perform the compaction operation in a transfer station, a facility that takes waste from small collection vehicles, strongly compacts it, and then puts it into large-capacity trucks, for delivery to distant destinations. One such truck can carry 30 tons of waste daily 100 km, making 200 km round trips, allowing time for the necessary loading and unloading operations.

The Solution Approach

The first step I took to solve the MSW management problem in the Centro Region was to formulate a general framework for intervention based on the following main ideas:

(1) To rely on generation-stage measures to reduce waste quantities before the collection stage;

(2) To use compaction operations in transfer stations to reduce waste volume after the collection stage;
(3) To reject separation, incineration, and composting operations (in the case of composting, the decision was based on unsatisfactory experiences in the past); and
(4) To define two levels of analysis, regional and local, to simplify the decision process.

At the regional level, I wanted to determine approximate locations and sizes for sanitary landfills and transfer stations and their catchment areas, taking into account their capacity limits and the maximum acceptable length of daily trips for both collection vehicles and transfer trucks.

My study brought some order to a chaotic situation.

At the local level, I wanted to determine exact locations for both types of facilities, taking into account their sizes and constraints dictated by the proximity of populated areas, transport infrastructures (notably airports), water sources, natural reserves, and so forth.

I considered the local level to be outside the scope of the study. This level of analysis is very important, because unless the authorities choose exact facility locations carefully, not-in-my-back-yard pressures can make it extremely difficult to implement any solutions. However, such decisions can be made at a later stage. Screening techniques developed with GIS tools, for instance, those described by Mendes and Silva [1996] (reporting a Portuguese application), Siddiqui, Everett, and Vieux [1996], and Siderelis [1991], may be useful at that stage.

The problems raised at the regional level fit into locational analysis, a major, fast-growing branch of OR that helps in identifying optimal locations (and sizes) for any kind of facilities.

Daskin [1995] and Love, Morris, and Wesolowski [1987] give detailed accounts of existing location models and solution methods. Hansen et al. [1987] and ReVelle and Laporte [1996] give concise overviews of the field and synthetize recent developments

Some models have been developed to help in the location of obnoxious facilities, like those for solid waste. Erkut and Neuman [1989] and Erkut and Verter [1996] survey the relevant literature extensively.

The main feature of the solid-waste-sector models is their multiobjective nature. One would like to locate sanitary landfills as far as possible from urban centers (maximum-distance objectives) and simultaneously as close as possible to producers of MSW to minimize costs (minimum-cost objectives).

I recognize that both kinds of objectives are relevant, but at the regional level of analysis, it is politically difficult to sustain maximum distance objectives because they lead to the concentration of sanitary landfills in areas (municipalities) with small populations, precisely those that produce very little waste. My view would be quite different if proximity to MSW threatened people's life or health, as does proximity to hazardous solid waste.

Based on these considerations, I postulated a minimum-cost objective for the problem and looked for a solution compatible with the region's administrative peculiarities, investment capabilities, and available managerial skills. (To be precise, I took into account only annual-equivalent costs of transfer stations and waste transport, because I assumed that sanitary landfill costs were proportional to landfill size above a given minimum capacity.)

The values I used for MSW generation were those expected for 2014, based on plausible growth rates for the population and for per capita MSW generation and assuming a significant increase in the recovery rates of glass and paper (25 percent for both materials against the present values of 12.5 percent for glass and two percent for paper). This increase is a regional policy goal, and a public education program is in place to promote it.

In achieving the objective of minimizing costs, I took the following constraints into account (Figure 3):

(1) Sanitary landfills have a minimum capacity of 70 tons per day to obtain scale economies.

(2) Transfer trucks make daily trips of no more than 100 km one way.

(3) Transfer stations have a maximum capacity of 70 tons per day to match a specific facility type, fully automated, and suited to local needs.

(4) Collection vehicles make daily trips of no more than 30 km one way.

(5) Sanitary landfills are to be located in the high-ranked municipalities of the regional urban hierarchy, those where, according to the development strategy stated in CCRC [1994], the main beneficial public facilities will be sited.

(6) Collection vehicles and transfer trucks must not cross the Serra da Estrela area, a mountainous region and natural park served only by narrow, winding roads.

(7) The Santa Comba Dão area should have its own sanitary landfill to support a local initiative already under way when I began this study.

(8) The Figueiró dos Vinhos area, which

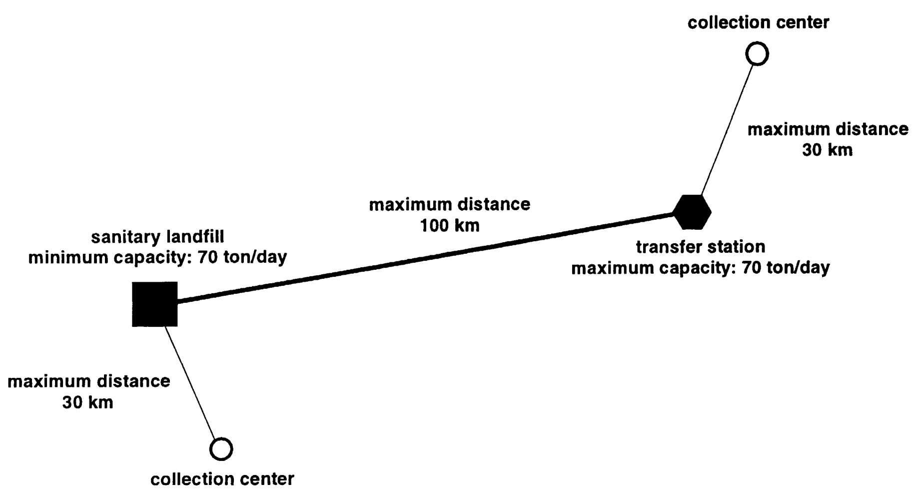

Figure 3: Constraints to be followed in locating sanitary landfills and transfer stations were established to take into consideration aspects relating to the capacity of both sanitary landfills and transfer stations and to the maximum daily trip length of collection vehicles and transfer trucks.

was already being served by Coimbra's solid waste company (ERSUC), should use either the Coimbra sanitary landfill (if, as expected, it is to exist) or have its own sanitary landfill.

The problem as I defined it combines elements of a p-median problem with what may be called a capacitated-facility-location problem with transshipments. I give the corresponding complex mixed-integer optimization model in the appendix.

The model has 9,764 variables, of which 104 are zero-one variables, and 9,933 constraints. These figures result from having 78 centers, 18 possible sites for sanitary-landfill locations, and 86 possible sites for transfer-station locations: three in Coimbra and three in Leiria; three in each of four centers, Aveiro, Castelo Branco, Ovar, and Viseu; and one in each of the 72 remaining centers.

At first, I supposed that it would be impossible to handle such a model with a general exact method, at least on a PC, the computer equipment I used for this study. I thus began by developing a greedy heuristic for that purpose, with a transshipment problem with capacity constraints to solve in each iteration. I obtained the initial results I presented to CCRC with this heuristic.

However, the combined effect of hardware and software evolution (the arrival of 133 MHz Pentiums and XPRESS-MP, Version 8) allowed me to solve the model to exact optimality with an acceptable computing effort.

Proposed Solution

I solved the model successively, increasing the number of sanitary landfills from

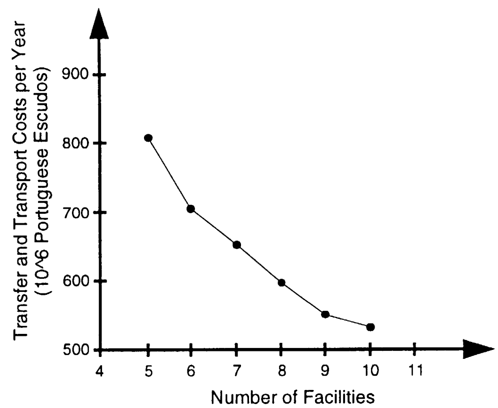

Figure 4: As the number of facilities increases, the costs for transfer and transport decreases.

five to 10 to evaluate the concomitant decrease in transfer-station and waste-transport costs (Figure 4). I set the minimum number of sanitary landfills at five to ensure an even distribution of waste discharge in the region. A smaller number would require some sanitary landfill or landfills to receive waste produced in areas perceived as remote. This would be unaceptable to the populations living near these facilities. I considered the maximum number, 10, to be the largest compatible with existing MSW managerial skills. Moreover, above this number, waste would have to be carried from the main urban centers to areas with small populations to satisfy the minimum capacity constraints. Or else some sanitary landfills would have to operate at uneconomic scales.

After analyzing the results in detail, the president of CCRC decided to propose the eight-landfills solution to the regional council, an institution consisting of representatives from all the municipalities of the region (Figure 5 and Table 1).

This solution pointed to sanitary landfills with capacities ranging from 283 (Aveiro) to 70 tons per day (Santa Comba Dão), and eight transfer stations, processing quantities of waste ranging from 70 (Águeda) to 14 tons per day (Figueiró dos Vinhos).

Three of the transfer stations, Águeda, Ovar, and Pombal, were not strictly necessary, in that, even in their absence, the maximum-trip-length constraints would not be violated. This means that the corresponding investment could be delayed, allowing the authorities to concentrate their initial expenditures on urgent sanitary landfills.

Recent Developments

The president of CCRC presented the proposed solution to the regional council shortly after the European Union approved the II Quadro Communitário de Apoio (Second European Union Aid Framework), which allotted money to the environmental area, particularly to investments for handling solid waste.

That presentation was the first step in a long negotiation process through which the municipalities slowly converged on the solution adopted in the Strategic Municipal Solid Waste Plan published by the Portuguese government (Ministério do Ambiente [1996]).

The solution I proposed and the solution adopted (Figure 6) differ, but the dif-

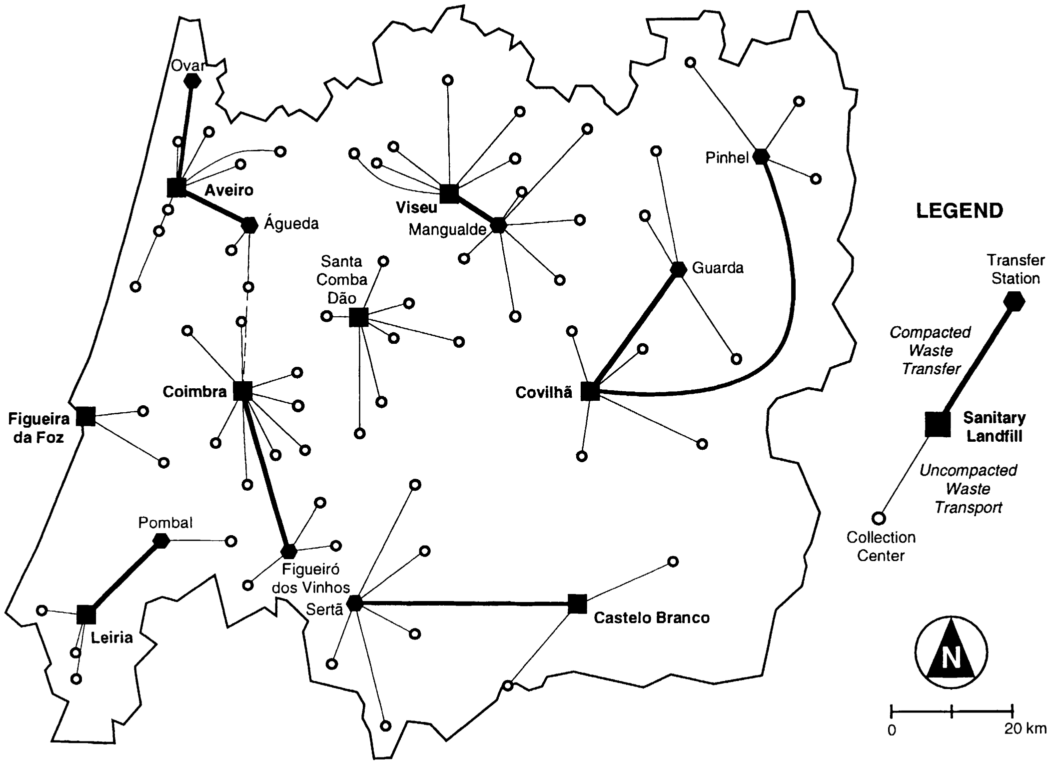

Figure 5: The proposed solution would assign 47 municipalities to sanitary landfills, while 31 municipalities would be assigned to transfer stations. The only situation of double assignment would occur with Anadia, a municipality that would be served mainly by the Águeda transfer station and by the Coimbra sanitary landfill.

Sanitary Landfills		Transfer Stations	
Location	Size (ton/day)	Location	Size (ton/day)
Aveiro	303	Águeda	70
Castelo Branco	87	Figueiró dos Vinhos	14
Coimbra	235	Guarda	49
Covilhã	144	Pinhel	21
Figueira da Foz	96	Sertã	28
Leiria	218	Mangualde	69
Santa Comba Dão	70	Ovar	54
Viseu	200	Pombal	47
Total	1,353	Total	352

Table 1: The proposed solution would allocate the 1,353 tons of MSW produced daily in the region to eight sanitary landfills, 26 percent of which would pass through one of the eight transfer stations to be built.

ferences are less important than they might seem. For example, for the western part of the region, the solution adopted contains only two systems, Alta Estremadura and Litoral Centro. These two systems were created by government acts 116/96 (August 6) and 166/96 (September 5), respectively, and are currently under implementation with a financial contribution from the European Union. Their operation has been committed to two companies, VALORLIS and ERSUC, for a period of 25 years. My proposal indicated four systems instead of two. But the difference lies mainly in the meaning given to the word system. In the solution adopted, it applies to the area a managerial unit manages, while in my proposed solution it applies to the area a sanitary landfill covers. In both solutions, there are four sanitary landfills at the same locations.

With respect to the other six systems, defined for areas where MSW problems are less important, the only fundamental decision the authorities made so far concerns the location of a sanitary landfill at Covilhã, a site specified in my proposed solution. The other systems will also have sanitary landfills, but their locations have not yet been decided.

Several aspects of the solution adopted in the Strategic Municipal Solid Waste Plan are open to change. According to the latest reports, changes are likely to bring that solution closer to my proposed solution. For instance, the set formed by the Viseu and Planalto Beirão systems in the solution adopted may become very similar to the Viseu and Santa Comba Dão systems of my study. And the Beira Serra system, which emerged from a peculiar context of municipal solidarity, will probably be dropped because of its uneconomic scale.

Even if this were not the case, the basic merit of the OR solution would remain: as the president of CCRC (now a director at ERSUC) recognizes, my study brought some order to a chaotic situation, with a credible, rational solution upon which municipalities are building their own, very similar, solutions.

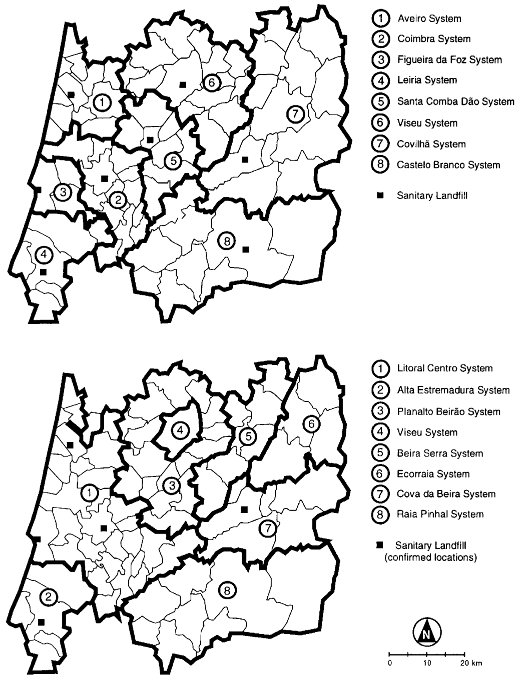

Figure 6: The solution I proposed (above) and the reference solution adopted in the Municipal Solid Waste Strategic Plan published by the Portuguese Government in October 1996 (below) are different, but not as different as they may appear. For instance, the four systems planned for the western part of the region have been transformed into two systems, but the two systems will contain four sanitary landfills, located where the proposed solution suggested they should be.

Acknowledgments

I thank Dr. Michael Rothkopf for encouraging me to submit this paper and for comments on the first version. I also thank Dr. Álvaro Seco, my colleague at the Department of Civil Engineering of the University of Coimbra, and three anonymous referees for their valuable remarks and suggestions.

APPENDIX

I formulated the regional waste management problem as follows:

$$\begin{aligned}\text{Min } C = & \sum_{j\in \mathbf{J}} \sum_{k\in \mathbf{K}} c_{tu}\cdot d_{1jk}\cdot w_{jk} \\ & + \sum_{j\in \mathbf{J}} \sum_{l\in \mathbf{L}} c_{tu}\cdot d_{2jl}\cdot v_{jl} \\ & + \sum_{k\in \mathbf{K}} \sum_{l\in \mathbf{L}} c_{tc}\cdot d_{3kl}\cdot x_{kl} \\ & + \sum_{k\in \mathbf{K}} c_f\cdot y_k \end{aligned} \tag{1}$$

subject to

$$\sum_{k\in \mathbf{K}} w_{jk} + \sum_{l\in \mathbf{L}} v_{jl} = q_j, \ \forall j \in \mathbf{J} \tag{2}$$

$$\sum_{j\in \mathbf{J}} w_{jk} = \sum_{l\in \mathbf{L}} x_{kl}, \ \forall k \in \mathbf{K} \tag{3}$$

$$w_{jk} \leq q_j\cdot y_k, \ \forall j \in \mathbf{J}, k \in \mathbf{K} \tag{4}$$

$$v_{jl} \leq q_j\cdot z_l, \ \forall j \in \mathbf{J}, l \in \mathbf{L} \tag{5}$$

$$x_{kl} \leq q\cdot z_l, \ \forall k \in \mathbf{K}, l \in \mathbf{L} \tag{6}$$

$$\sum_{l\in \mathbf{L}} z_l \leq p \tag{7}$$

$$\sum_{j\in \mathbf{J}} w_{jk} \leq S_{1\max}, \ \forall k \in \mathbf{K} \tag{8}$$

$$\sum_{j\in \mathbf{J}} v_{jl} + \sum_{k\in \mathbf{K}} x_{kl} \geqslant S_{2\min}\cdot z_l, \ \forall l \in \mathbf{L} \tag{9}$$

$$z_{S.C.Dão} = 1 \tag{10}$$

$$z_{F.Vinhos} + y_{F.Vinhos} = 1 \tag{11}$$

$$x_{F.Vinhos,Sertã} = 0 \tag{12}$$

$$x_{F.Vinhos,Pombal} = 0 \tag{13}$$

$$w_{jk}, v_{jl}, x_{kl} \geqslant 0, \ \forall j \in \mathbf{J}, k \in \mathbf{K}, l \in \mathbf{L}$$

$$y_k, z_l \in \{0, 1\}, \ \forall k \in \mathbf{K}, l \in \mathbf{L},$$

where:

C: total annual-equivalent cost;

$\mathbf{J}$: set of collection centers ($j = 1, \ldots, J$);

$\mathbf{K}$: set of sites for the location of transfer stations ($k = 1, \ldots, K$);

$\mathbf{L}$: set of sites for the location of sanitary landfills ($l = 1, \ldots, L$);

w_{jk}: quantity (tons) of waste generated at center j and carried to a transfer station located at site k;

v_{jl}: quantity (tons) of waste generated at center j and carried to a sanitary landfill located at site l;

x_{kl}: quantity (tons) of waste sent from a transfer station located at site k and carried to a sanitary landfill located at site l;

$y_k = 1$ if a transfer station is located at site k, otherwise $y_k = 0$;

$z_l = 1$ if a sanitary landfill is located at site l, otherwise $z_l = 0$;

c_{tu}: transport costs for uncompacted waste;

c_{tc}: transport costs for compacted waste;

$d_{1jk} = d_{jk}$ (distance between center j and site k) if $d_{jk} \leq 30$ km, otherwise $d_{1jk} = \infty$;

$d_{2jl} = d_{jl}$ (distance between center j and site l) if $d_{jl} \leq 30$ km, otherwise $d_{2jl} = \infty$;

$d_{3kl} = d_{kl}$ (distance between center k and l) if $d_{kl} \leq 100$ km, otherwise $d_{3kl} = \infty$;

c_f: (fixed) cost of a transfer station;

q_j: quantity of waste generated at center j;

q: total quantity of waste generated in the region;

p: maximum number of sanitary landfills;

$S_{1\max}$: maximum capacity of a transfer station;

$S_{2\min}$: minimum capacity of a sanitary landfill.

In this mixed-integer-programming model, function (1) expresses the objective of minimizing total costs, assuming that above the minimum capacity, sanitary landfill costs are identical everywhere and proportional to capacity. Transport costs, defined separately for compacted and uncompacted waste, include fuel and manpower, as well as vehicle maintenance and depreciation. In calculating costs, I used Euclidian distances. The road network is being fully renovated, and I thought this would represent future transport conditions quite well. Transfer station costs are fixed, as they correspond to a specific type of station, well suited to local needs.

Constraints (2) ensure that the waste generated at each collection center will be sent to either a sanitary landfill or a transfer station, and constraints (3) guarantee that all the waste sent to a transfer station will be carried to a sanitary landfill.

Constraints (4) and (5) ensure that collection centers will be linked to open sites (disposing of either a sanitary landfill or a transfer station); constraints (6) guarantee that transfer stations will be linked to open sanitary landfills.

Constraint (7) defines a maximum of p for the number of sanitary landfills.

Constraints (8) ensure that maximum capacity limits of transfer stations will be observed, and constraints (9) guarantee that minimum capacity limits of sanitary landfills will be considered.

Constraint (10) ensures that, as required, the Santa Comba Dão area will have its own sanitary landfill. Constraint (11) guarantees that the Figueiró dos Vinhos area will either have its own sanitary landfill or a transfer station. In case there is a transfer station at Figueiró dos Vinhos, constraints (12) and (13) rule out shipments from this station to Sertã or Pombal, forcing shipments to Coimbra.

(*Note*: Data used to run the model can be obtained from the author by writing to antunes@dec.uc.pt.)

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Alberto Santos, Director, ERSUC, Resíduos Sólidos do Centro, S.A., Coimbra, Portugal, writes: "Though being presently a director at ERSUC, the Centro Urban Solid Waste Corporation, I was the president of CCRC, the Portuguese Central Region Planning Agency, at the time António Antunes prepared the study he reports in his paper. The study is only one of the outcomes of a research project developed within the framework of a Cooperation Agreement signed in 1994 by the rector of the University of Coimbra and myself (in representation of CCRC), and involving both the solid waste sector and the water supply sector.

"Both sectors were requiring important decisions to be taken, and, particularly in the solid waste sector, the decision-making environment was quite confused, with isolated, noncoordinated municipal initiatives taking place all over the region.

"This was the main reason why we needed the study, and its main merit was to supply a firm basis on which to start discussion between the many parties involved (government, municipalities, nongovernmental organizations, etc.).

"All the fundamental aspects of Antunes' proposal have been retained, but, of course, some adjustments were required, and other ones will surely be necessary in the future. For instance, the waste collected at the transfer station of Avelar (near Figueiró dos Vinhos) will be sent to a sanitary landfill in Figueira da Foz, and not to Coimbra. This happens especially because the road linking Avelar and Figueira da Foz is better than the one connecting Avelar and Coimbra (which is being slowly renovated).

"To conclude, I would say that the Antunes' study gave a significant contribution to the solution of the serious solid waste problems of the Central Region, and is helping to promote a better environment in our country."