ANALYSIS OF SOLID-WASTE SYSTEMS IN A RURAL SETTING

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The U. S. Forest Service is currently upgrading the solid-waste disposal methods used in its 153 national forests. The technique consists of collecting refuse at camping and picnicking areas by using trucks. The trucks then haul the solid waste to conveniently located sanitary landfills where it is compacted and buried. Preliminary analysis of this approach in a test forest showed that cost savings of as much as a third are possible. To minimize total cost, we have constructed a deterministic crew-scheduling model that consists of a mixed integer linear programming formulation. Areas to be serviced are introduced as nodes in a network, and connective roads constitute the network links. The necessity for servicing all camp areas, the limited capacity of trucks, and the limited working day of crews serve as a set of constraints. In addition, crews start and end their tours at headquarters. Costs are associated with both the total network coverage and the landfill operation. The variables under management control, such as crew size, truck capacity, and collection frequency, are tested parametrically; i.e., the optimum schedule is evaluated each time a parameter is changed. The procedure permits an integrated regional plan to be compared with a collection of subregional plans.

•IN 1970, the national forests hosted more than 172 million recreation visitor-days. Visitor-days are the product of the number of visitors and their lengths of stay divided by 12 hours. Currently, more than $12 million annually is spent to handle solid wastes, the bulk of which is created by recreational visitors.

About 96 percent of these costs are for collection and hauling. The introduction of higher standards of disposal at centrally located sanitary landfills necessitates higher expenditures for transport as well as for disposal. Hence, more comprehensive methods for analyzing solid-waste systems are needed to keep costs to a minimum.

The goal of this study is the development of methods for examining alternative plans and schedules for storing, collecting, transporting, and disposing of refuse in a rural setting. The rural setting is characterized by widely dispersed waste generating points with small volumes at each point. This sharply contrasts with the urban setting where waste generating points are so closely spaced as to present nearly a continuous distribution along a city street. Refuse resulting from harvesting timber and constructing roads is not within the scope of this study.

Refuse is generated largely during short recreation seasons that last only 3 months in some places. Hence, the collection schedule must be changed, sometimes monthly, to conform to the seasonality of use. Refuse is usually stored in cylindrical cans (often with disposable plastic liners) that are handled manually or in large metal bins that are handled mechanically. Compaction of refuse is never done at the site of generation. Special containers are sometimes used to keep the solid waste safe from wildlife.

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Refuse is transported in open trucks or compactor trucks periodically; pickup cycles vary in frequency from daily to weekly depending on the attractiveness of the refuse to animals and its unattractiveness to visitors. Although transfer stations are not presently used, our methods of analysis permit that possibility.

In the more densely used recreation areas where a truck makes more than one daily trip to the landfill, the trip may be made by only part of the crew while the remainder services storage containers. This permits hauling to be separated from container servicing. However, if the two tasks are not coordinated, double handling becomes necessary. In this case, a transfer station that employs mechanical handling is usually necessary because the thin plastic liners will not tolerate the abuse of double handling. It is our assumption that many designers will choose a system configuration in which the two tasks are performed by the same crew. For the present, this is the hypothesis used throughout our study.

Disposal by incineration is not currently preferred. Because the composition of recreational solid waste is high in moisture and low in flammability, the large amount of energy required for volume reduction by means of incineration is very expensive. Therefore, the preferred method of disposal is the use of a sanitary landfill with unloading, compacting, and covering all being accomplished on the same day.

METHODS OF ANALYSIS

Waste generating rates were examined in a 1969 field study described by Spooner (5). His results established a direct functional dependence of the amount of generated waste on the number and activity of visitors using a recreational facility. The results can be used without regard to geographical location. These findings permit the U. S. Forest Service to estimate the amount of waste by counting people.

Collection times were obtained from a report by Little (2) and from our own field studies. Collection times depend on crew size, truck size, and number of clustered containers that are empty. The number of containers needed depends on the frequency of collection as well as on the frequency of campsite use.

The time required for a tractor to compact and cover material at landfills was studied by Little (2). He found that the total cost consists of a fixed setup cost for readying equipment and terrain augmented by linear function of the amount of material.

The most difficult part of the analysis is selecting routes; there are many alternatives, and each requires a large number of calculations. Our approach is to fix the landfill locations, crew sizes, collection frequency, and truck size and then determine crew route schedules. This is repeated by using a different choice of landfill location and/or crew size to obtain alternative solutions whose costs may be compared.

We recognized the stochastic nature of recreation use. Spooner (5) indicated that use varies during any week as well as over the entire season. Use also varies among locations. However, we chose to treat the design as a deterministic problem rather than a stochastic problem because schedules and facilities cannot be changed as frequently as use varies. We feel, however, that economies can be obtained by changing the schedule, for example, each month or two. This can sometimes be accomplished by closing some campsites during slack periods or by sealing containers. We also found situations where it is cheaper to permit partial servicing of a campsite on one tour (leaving the remainder for the next tour), thereby using more effectively the available truck capacity and time. We call this the "partial pickup" policy in contrast to the "total pickup" policy that does not permit partial servicing of a campground.

Whenever the schedule permits the landfill to be operated less frequently than daily, the dozer-tractor may be engaged elsewhere for other tasks. This permits a dozer to be shuttled between landfills. A simple break-even analysis indicates when the cost of a number of trips for one dozer is less than the cost of using two dozers.

The methods developed may be used to examine regional systems, which yields the costs to each agency. Regional programs are often desirable because of economies of scale and because publicly owned land is often the only feasible place available for disposal. (Federal agencies cannot legally contract for disposal by private entrepreneurs if their method does not meet federal standards.) The ability to examine regional

and subregional systems is useful for exploring the effects of changing crew headquarters locations.

We use the notion of system boundaries to locate generating sites and landfills that appear as nodes on a transport network. The network defines our system boundaries, and it may be arbitrarily partitioned into several subsystems whose boundaries may be compared with existing administrative boundaries. Partitioning may also simplify the computations where natural clusters of generating points are separated by very long distances—a situation typically encountered in a rural setting.

Locating landfills by the use of the centroid notion (found in classical mechanics) was not useful because the travel time between a generating point and the landfill is only defined along links of the transport network. We also found that landfills must be located with a cautious eye toward potential groundwater pollution and future uses of the site Hence, it became necessary to treat the landfill locations as parameters subject to change from time to time rather than as variables.

COST DIFFERENCES

We tested 11 different configurations on the Texas National Forests by means of hand computations. (The construction of access roads to the landfill was not included in the cost.) We found, during the 6-month peak season, changes in (a) truck capacity, amounting to about $6,000; (b) number of landfills, about $2,000; and (c) frequency of collection, about $7,000. The least expensive configuration cost $19,200, and the most expensive cost $29,400.

MATHEMATICAL MODEL EXAMPLE

Space permits only one problem to be presented—the partial pickup problem formulated as a zero-one, mixed-integer linear programming problem whose solution would yield the optimal schedule for routing crews so as to minimize total collection cost. This problem and the total pickup problem are not tractable by the usual solution methods because of their large scale. In a future publication, we shall discuss some approaches for solving them.

The version of partial pickup problem presented here assumes that the landfill is sufficiently close to crew headquarters such that the travel time between headquarters and the landfill is negligible. The reason is for simplicity of exposition. This assumption means there is only one type of tour, one that originates and ends at headquarters. Where the headquarters is not close to the landfill, there are two types of tours—those that originate at headquarters and those that originate at the landfill. We also assume a single truck size, single crew size, and single collection frequency. The length of the working day is fixed; there is no overtime option or penalty for unused crew time.

Notation

T_{ij} = least travel time from point i to point j (in minutes) and point 0, the origin, is the headquarters location;
t_j = service time at point j (in minutes);
w_j = waste production at point j (in cubic yards);
d = maximum working time per day (in minutes);
v = volume capacity of the truck (in cubic yards);
y_{jk} = fraction of site j serviced by crew k;
$x_{ijk\ell}$ = fraction of the link between i and j that is used by crew k on the ℓth leg of its tour;
N = number of crews; and
M = number of waste generation points.

Constraints

1. $$\sum_{j=1}^{M} w_j y_{jk} \le v, \quad \text{for } k = 1, 2, \ldots, N$$

Explanation: Crew k may not exceed its truck capacity during its tour.

2. $$\sum_{i=0}^{M} \sum_{j=0}^{M} T_{ij} \sum_{\ell=1}^{M+1} x_{ijk\ell} + \sum_{j=1}^{M} t_j y_{jk} \le d, \quad \text{for } k = 1, 2, \ldots, N$$

Explanation: Crew k may not exceed its maximum daily working time during its tour.

3. $$\sum_{k=1}^{N} y_{jk} = 1, \quad \text{for } j = 1, 2, \ldots, M$$

Explanation: Each site must be fully serviced.

4. $$\sum_{j=1}^{M} x_{0jk\ell} = 1, \quad \text{for } k = 1, 2, \ldots, N$$

Explanation: Crew k must start from the origin (headquarters) during the first leg of its tour.

5. $$\sum_{i=1}^{M} \sum_{\ell=2}^{M+1} x_{i0k\ell} = 1, \quad \text{for } k = 1, 2, \ldots, N$$

Explanation: Crew k must return to the origin after the first leg of its tour (note that there are zero maximum of M + 1 legs on a crew tour if the crew services all waste generating points).

6. $$x_{0jk_1} - \sum_{i=0}^{M} x_{jik_2} = 0, \quad \text{for } \begin{matrix} j = 1, 2, \ldots, M \\ k = 1, 2, \ldots, N \end{matrix}$$

Explanation: Crew k going from the origin to some point j during the first leg of its tour must depart from point j during the second leg of its tour.

7. $$\sum_{i=1}^{M} x_{ijk\ell} - \sum_{i=0}^{M} x_{jik(\ell+1)} = 0, \quad \text{for } \begin{matrix} j = 1, 2, \ldots, M \\ k = 1, 2, \ldots, N \\ \ell = 2, 3, \ldots, M \end{matrix}$$

Explanation: Crew k arriving from point i (other than the origin) at point j during the ℓth ($\ell > 1$) leg of its tour must depart from point j during the ($\ell + 1$)th leg of its tour. Its destination may, however, include the origin.

8. $$\sum_{i=0}^{M} \sum_{\ell=1}^{M} x_{ijk\ell} - y_{jk} \ge 0, \quad \text{for } \begin{matrix} j = 1, 2, \ldots, M \\ k = 1, 2, \ldots, N \end{matrix}$$

Explanation: If crew k is to service site j (either fully or in part), crew k must arrive at site j prior to the (M + 1)th leg of its tour. [If there exists an (M + 1)th leg on the tour, it would constitute a return to the origin.]

9. $x_{ijk\ell} = 0$ or 1, for all i, j, k, ℓ

Explanation: Either crew k travels along a link during the ℓth leg of its tour or it does not.

10. $y_{jk} \ge 0$, for all j, k

Explanation: The fraction of site serviced by crew must be non-negative. It is guaranteed not to exceed unity by constraint 3.

11. $i \neq j$ for any $x_{ijk\ell}$

Explanation: A crew does not stay at a point during a leg of its travel.

Objective Function

$$\text{Minimize} \sum_{i=0}^{M} \sum_{j=0}^{M} T_{ij} \sum_{k=1}^{N} \sum_{\ell=1}^{M+1} x_{ijk\ell}$$

Explanation: Because total service time at each site is fixed, the cost of this service is constant, and its contribution need not appear in the objective function. Because traveling cost is proportional to travel time, it suffices to minimize the latter.

Comment

To investigate the problem fully, we have to consider several parameters:

1. If N is too small, the problem becomes unfeasible and the number of crews must be increased, whereas an N that is too large may actually be inefficient and should be reduced, one crew at a time until unfeasibility is reached.
2. Factors that affect service time (t_j) and waste volume (w_j) at each site must be considered. These factors are seasonal use, collection frequency, and crew size (which affects service time only).
3. Varying truck sizes should be investigated because they affect constraint 1.

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DISCUSSION

W. B. Drake, Kentucky Department of Highways

I want to congratulate the authors for an interesting analysis of collection systems for solid waste in the national forest setting. This type of analysis should enable the proper economic decisions to be made when sufficient historical data have been compiled.

There are some similar situations and decisions pending currently in the Kentucky Department of Highways. We have numerous parks, forest lands, and recreational areas in Kentucky. Our litter pickup cost, which has been increasing in recent years, amounted to $1,520,714 for fiscal year 1970-71.

There has been a concerted effort made by anti-pollution commissions and environmentalists to eliminate or minimize water and air pollution from open dumps, sanitary landfills, and minimum-efficiency incinerators. The result has been that many small governmental agency dumps and disposal areas have been closed for noncompliance, which leaves some areas with only private means for the disposal of solid waste.

An interesting situation occurred along these lines recently. One of our highway administrators was vacationing at a privately developed commercial campsite on a major lake. There was displayed on the mirror in the bathroom a detailed map with the following instructions:

> Please leave this cabin in the same condition that you found it. You are to take your trash and garbage in the plastic bags provided to the Department of Highways litter barrel shown on this sketch.

Although the purpose of the litter barrels is to collect trash and litter from cars traveling the highways, we find many instances where the barrels are being misused. The story is told that an enterprising citizen in one area was using his small pickup truck to assist some of his neighbors in hauling their litter to our barrels.

We are most interested in the recent action of some state highway agencies to eliminate public garbage collection and disposal. These contrary thoughts arise from doubts that highway departments can or should afford the burden of providing a public disposal system.

Innovations from the standpoint of convenience and public obedience are desirable. Perhaps optimization from a systems point of view will eventually and more clearly define the tasks, costs, and responsibilities involved in the collection and transportation of solid waste to a disposal facility. Again, it appears to me that further innovation may be necessary.

Charles F. Riebe, National Park Service

It appears that the authors have developed a deterministic model that partially satisfies the stated goal. The mathematical model presented in their report includes only those variables or parameters that provide for the collection and transportation of refuse and seems to exclude the capability of specifically examining scheduling, storage schemes, and disposal operations. This does not negate its usefulness for examining alternative refuse collection schemes and their respective costs.

The model is limited by several valid constraints that are specifically stated, but there are also some restrictions that result from the basic assumptions that may affect the sensitivity and effectiveness of the model.

Perhaps the greatest value of the paper is the idea of a regional collection scheme that includes several subregions. I have interpreted this idea to mean that regions should be composed of different public and private jurisdictions rather than just geographical locations under one jurisdiction or managerial authority.

The authors point out the desirability of such a scheme because of economies of scale and the possibility of public land being the sole source of a disposal site.

It is time for collecting agencies to begin considering the problem in terms of rural waste, i.e., waste from all rural sources—forests, parks, recreation sites, rural households, and the connecting roads and roadsides. This would, of necessity, have to be considered on the basis of individual regional schemes and would require great initiative.

It appears that the mathematical model presented is sufficiently general to be applied to a regional scheme involving several managerial or supervisory jurisdictions bound together under a common agreement for collection and disposal of waste. One limitation in its use would be the requirement for a single headquarters and a single disposal site. It is possible that several points of origin and disposal should be considered in any such regional scheme because of the constraints that could result from using only one. The model presented has a headquarters location but does not include a disposal site; however, a collection site variable or parameter could possibly be used

as a substitute. This may result in reduction of sensitivity of the model in its present form.

Further study needs to be done of staging points and rural collection practices. We can safely assume that those who dispose of household waste in roadside cans in rural areas either do not have satisfactory disposal systems locally or are just plain inconsiderate. I can recall a situation where roadside cans were continually used for household waste because the home owners considered the price of 40 cents to incinerate a 32-gallon can of trash too high. When local authorities arrested several violators for such practice, the garbage was then strewn along the roadside or found in the brush.

The problem of household waste being disposed of in roadside litter barrels could be examined by the mathematical model developed by Kirby and Hirsch.

If the highway department became the waste collection and disposal authority by agreement of those involved, collection schemes could be developed and examined on a cost basis that would be in the best interest of all those concerned.

Although I have not personally tried the model presented, it is my opinion that it will provide a satisfactory method for examining alternative schemes of waste collection in rural areas. Further analysis may indicate that other variables are desirable and that the assumptions made in developing the model are too restrictive.

AUTHORS' CLOSURE

The authors wish to thank Drake and Riebe for their interesting discussions. Riebe deserves credit for extending the discussion of regional systems that our paper briefly introduced. He raises questions about some of the details of our approach that we will clarify briefly. First, the term disposal site could be substituted for landfill. A disposal site then may be either a landfill or a transfer station. If it is the latter, the transfer stations become the service locations of another network. The second network, with its own collection routes and disposal points, may be treated separately from the first network. Our approach may be used for analyzing each network in turn. Viewed in this way, the analysis of the first network is independent of the type of disposal point—landfill or transfer station.

The reason for presenting the mathematical formulation with one headquarters and one disposal point is that it is the simplest of several cases we have analyzed in this way. This formulation is useful in its own right for networks that can be partitioned naturally, i.e., networks characterized by widely separated clusters of collection points. In such a case, each cluster is treated separately. Where such natural clustering does not exist, other more complicated versions are required.

The general approach described in the paper is being used currently in the U. S. Forest Service—smaller systems by means of manual calculations and larger systems by means of a computer program named SOWAD (solid-waste design). This program is designed for the multiple headquarters and multiple disposal situation. It employs a heuristic logic rather than a mathematical programming formulation because there appear to be no feasible methods for solving large-scale problems of the type formulated in our paper.