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AN OPTIMIZATION MODEL FOR
MODULAR INCINERATION AND TRANSFER STATION
LOCATION IN MUNICIPAL SOLID WASTE SYSTEMS

BY

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RESEARCH REPORT

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ABSTRACT

Facility location models presently available in solid waste management are reviewed. From these models, one is adapted and modified to optimally locate the modular incinerator plants and transfer stations in municipal solid waste systems. The criteria for optimization is developed in terms of minimum total costs of the system. The generation and composition of municipal solid waste at present, and projected estimates into the future, through the year 2000, are also presented. Recommendations are made for the use of modular incinerators and conservation of landfills and use of the optimization model for locating incinerator plants and transfer stations by the municipal solid waste managers.

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I. INTRODUCTION

More and more attention has been given to the pollution of the environment in the recent years. Water and air pollution have long been receiving recognition. As a result, significant control measurement has been proposed, and a comprehensive volume of legislation has been passed requiring pollution control and prevention in the water and air environment systems. The "third pollution", as has been called by some, is the pollution of the land surfaces. This third pollution consists essentially of disposal of that which is termed solid waste (Hagerty et al. 1973, p. 1).

The growing severity of the solid waste problem has caused, at least on the part of the federal government, a broader awareness of the need for drastic measures, both fiscal and technological, to alleviate the problem. With the passage of the Solid Waste Disposal Act in 1965, some concrete action was taken to control and prevent solid waste pollution.

In the intervening period, the movement to control and prevent pollution of the land has accelerated rapidly and much has been accomplished. The general public no longer is apathetic, but rather concerns itself with the problem of collection and disposal of solid waste. Considerable amounts of money have been spent in the investigation of the problem and in the planning of solutions. This has led to the development of new technologies in solid waste management.

Statement of the Problem

There are many factors affecting growth of the municipal solid waste. One is the increasing population of the United States in general and that of urban areas in particular. Another is the economic growth resulting in production of more goods. The joint effect of these two factors and the decrease in materials reclamation practices has resulted in an increase of solid waste generation. A third factor is the change in the industrial technologies. This factor not only affected the increase in the magnitude of solid waste but also has changed its composition as well. For example, the increased use of plastics and metal containers has caused the proportion which is biodegradable to decrease.

The goal of the municipal solid waste manager is to achieve some desired level of service at a minimum cost. To achieve this goal, the type of questions he might ask are as follows (Marks and Liebman 1970):

1. What are the goals of the system? What frequency of collection and types of service should be offered by the system? How will changing the service affect cost?
2. What types of vehicles should be used, and how many?
3. How many personnel are needed, and what should their duties and work rules be?
4. What route should be assigned to each vehicle? How should the city be divided into administrative subgroups.
5. Are there parameters of the system to which system costs and variables are particularly sensitive?

6. If there is additional money available for research, into what aspect of the system should further study be encouraged?
7. Should there be intermediate transfer stations for the deployment of wastes to more specialized transport vehicles? Where should they be located and what type of equipment should they contain?
8. What type of transport vehicles would be used in the transfer of waste from a transfer station to the final disposal?
9. What type of disposal alternative should be chosen and where should it be located?
10. What would be the effect on the system of new technology in in-house waste reduction? In new disposal technology?
11. How will the stochastic nature of waste generation affect the analysis? How will the solution change as the area to be served continues to grow and spread?
12. What are the effects of political, social and economic constraints? How much should be spent on aesthetic factors? Is regional grouping a feasible alternative?

To answer all these questions, the manager must build some form of model capable of handling the system. The complexity of the system may make detailed modeling impractical. However, by simplifying assumptions, models may be developed that will approximate the problem and aid the manager in decision making.

Solution

There are four basic categories of criteria in decision making in the solid waste field (U.S. EPA 1976): Cost, environmental factors,

resource conservation, and institutional factors. The key points in each of these categories are as follows:

- * Cost

- Operating and maintenance

- Capital (initial investment)

- * Environmental factors

- Water pollution

- Air pollution

- Other health factors

- Aesthetic considerations

- * Resource conservation

- Energy

- Material

- Land

- * Institutional factors

- Political feasibility

- Legislative constraints

- Administrative simplicity

The cost criteria are among the most important ones. Environmental criteria are most important in the areas of storage and disposal. Citizens are becoming increasingly concerned with resource conservation due to the energy shortage in recent years. Certain institutional factors are sometimes the most important criteria. Managers should always be concerned with these factors since they may prevent a particular decision or eliminate an alternative.

Solid waste management may be divided into four major

functions: collection, transport, processing, and disposal (U.S. EPA 1976). Figure 1 shows the flow of solid waste from collection to disposal. These functions must be considered as integrated and coordinated activities rather than individual and independent operations. However, insofar as collection functions could remain the same regardless of the processing method chosen, this report will not be concerned with the collection function. Solid waste may be collected and transferred to disposal sites unprocessed. Or, it may be processed before disposal. Solid waste processes involve volume and weight reduction. They include: incineration with or without heat recovery, pyrolysis, use of solid waste as fuel in utility or industrial boilers, and materials recovery. Of these processes, only incineration will be considered in this report because it is widely used by municipalities. Other processes are yet in various stages of development.

The two most commonly used methods of solid waste disposal by municipalities are sanitary landfilling and incineration. Municipal incinerators are of two types: conventional incinerators with capacities of 50 to 300 tons per day, and small or modular incinerators with capacities of 5 to 50 tons per day. According to a U.S. EPA report (1976), the use of conventional incinerators is on the decline because of high capital and operating costs and stringent air pollution requirements, while the use of small incinerators is increasing among communities of various sizes. Sanitary landfills are a necessary part of all solid waste management systems. Due to the scarcity of land, if it is available at all, and its premium costs, this writer

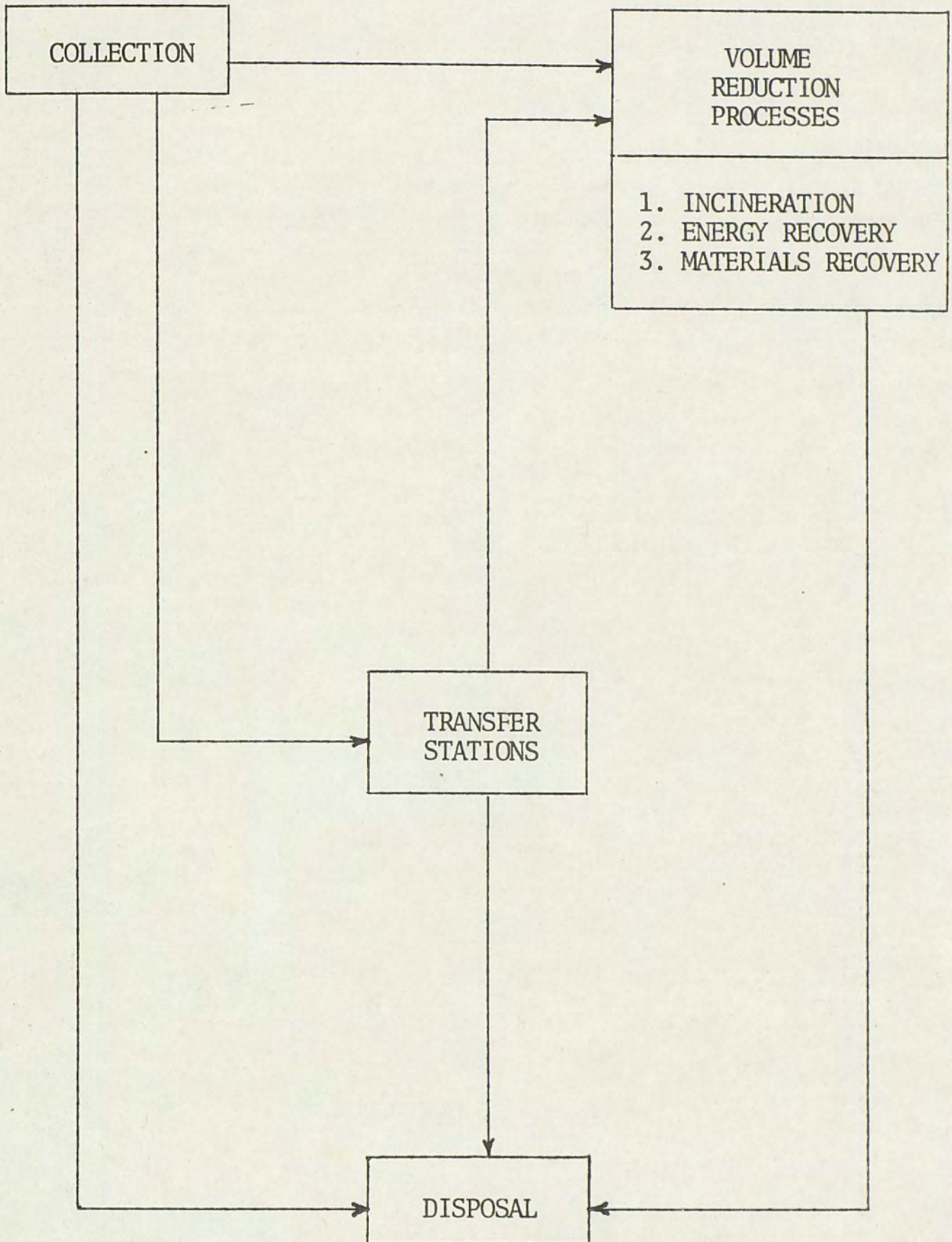


Fig. 1. Flow and Solid Waste from Collection to Disposal

believes sanitary landfills should not be used for unprocessed waste, and that they should be conserved for reduced residues from the waste processing plants.

In many urban areas, acceptable landfill sites have become difficult to obtain and the expense of direct hauling of waste from collection points to landfill sites has been rising steadily. The municipal solid waste managers should consider, as alternatives, the use of modular incinerators and transfer stations. Some municipalities are already using modular incinerators with success (Hofmann et al., 1976).

To provide the total burning capacity required by a municipality, a system may be developed to install modular units from two to eight in each plant optimally located. Such a modular approach will provide greater flexibility for small and medium sized cities than exists with the large conventional incinerator plants. As an added feature, it provides flexibility for expansion as the city expands its waste generation. For certain communities with large areas and not necessarily with uniform population density, the modular plant approach will permit the installation of relatively inexpensive satellite plants, resulting in reduced hauling costs to incinerators from collection points or transfer stations.

Objective

The objective of this report is to survey the solid waste management models presently available and adapt one which could aid the manager in choosing the economically optimal plan, from among a

large number of alternatives, to locate the incinerator facilities and transfer stations over the feasible areas in municipalities. The decision criteria will be developed in terms of minimum total cost of operating the system. The model will not be sufficient to provide a final answer to the problem. Its greatest benefit will be to assist decision makers in evaluating the alternatives for trade-offs between the costs and level of service desired.

In the design of the incinerator facilities and number of modular units required for each plant, the knowledge of quantities and qualities of the municipal solid waste, at present and in the future, are essential. The size of the incinerator plants and transfer station facilities that are to be built at present, and their expansions in the future, depend on generation of waste. Similarly, the design of these facilities for environmental protection measures and energy recovery capabilities depend on the composition of waste. These variables, generation and composition of solid waste, affect the model in terms of capacity and operating costs of the facilities that are to be optimally located. The generation and composition of the municipal solid waste, at present and the projected estimates into the future, are discussed in the next chapter.

II. BACKGROUND

The quantities and qualities of refuse generated now and in the future have significant implications regarding the overall management of solid waste. Its physical and chemical nature should be considered necessary for a variety of reasons. The number and capacities of incinerators to be constructed, the selection of other solid waste disposal processes, and modifications to equipment and operating practices for existing facilities will be dependent upon the characteristics of the generated refuse. This section presents the basic data pertaining to the generation and composition of the solid waste.

Solid Waste Generation

National surveys (OSWM 1968) show that the average amount of solid waste collected in the United States in 1968, the most recent year for which such data is available, was about 5.32 pounds per person per day. Table 1 (Hagerty et al. 1973, Table 2-2) shows survey results for determinations of quantities of waste collected.

These figures are approximate and include only material known to be collected. Household, commercial, industrial, demolition and other solid waste that was transported to disposal sites or disposed of by the generating party are not included. A report from a consensus of various sources (Baum and Parker 1973, p. 4) shows the growth in collectable refuse (residential, commercial and industrial wastes --

excluding agricultural and mineral wastes) in the United States as follows:

TABLE 1
SOLID WASTE COLLECTED DAILY, 1968

Item	National Average (lb/cap/day)		
	Urban	Rural	Total
Domestic	1.26	0.72	1.14
Commerical	0.46	0.11	0.38
Combined	2.63	2.60	2.63
Industrial	0.65	0.37	0.59
Demolition-Construction	0.23	0.02	0.18
Street Sweepings	0.11	0.03	0.09
Miscellaneous	<u>0.38</u>	<u>0.08</u>	<u>0.31</u>
Totals	5.72	3.93	5.32

Year	1950	1960	1970	1980
Total (million tons)	105	135	195	230

Municipal Solid Waste Composition

Perhaps the best available analysis of the municipal solid waste composition is from the study on this subject by Niessen and Chansky (1970), and Niessen and Alsobrook (1972). The material of this section is taken from these references.

Samples collected from 41 communities and municipalities throughout the United States in 1968, representing about 60 percent of

the national population, were analyzed for the primary components of each of the refuse categories. Table 2 (Niessen et al. 1970, Table 10) shows refuse categories and descriptions.

TABLE 2
REFUSE DESCRIPTION

Category	Description
Glass	Bottles (primarily)
Metal	Cans, wire, and foil
Paper	Various types, some with filters
Plastics	Polyvinyl Chloride, Polyethylene, Styrene, etc., as found in packaging, housewares, furniture, toys, and nonwoven synthetics
Leather, rubber	Shoes, tires, toys, etc.
Textiles	Cellulosic, protein, woven synthetics
Wood	Wooden packaging, furniture, logs, twigs
Food wastes	Garbage
Miscellaneous	Inorganic ash, stones, dust
Yard wastes	Grass, brush, shrub trimmings

The refuse collected was from 11 basic types:

- | | | |
|----------------|---------------------------------|------------------|
| * Household | * Institutional | * Park and Beach |
| * Commercial | * Demolitional and Construction | * Catch Basin |
| * Industrial | * Street and Alley | * Sewage Solids |
| * Agricultural | * Tree and Landscaping | |

In general, household and commercial refuse comprise the majority of the refuse collected. Inasmuch as the study was concerned only with municipal refuse, the industrial and agricultural types were excluded from the analysis.

The composition analysis showed a wide variation in average composition of yard wastes and miscellaneous categories. "Yard Wastes" fraction was found to be very sensitive to both geographical location and the season of the year when the sample was taken. The "Miscellaneous" fraction was found to be dependent upon local practices and regulations that are concerned with collection of demolition and other such wastes. The other eight categories seemed to be less dependent upon seasonal and geographical variation. The compositions of "Yard Wastes" and "Miscellaneous" refuse collected were adjusted to reflect the effects on climate and locations. The seasonal average of municipal refuse composition for 1970 was estimated as shown in Table 3 (Niessen et al. 1972, Table 5).

The moisture content of refuse changes from the time it is discarded to the time it is fired in an incinerator. Solid waste may either lose or absorb moisture in this interval. Paper, for example, may absorb significant quantities of moisture from food wastes, while glass may not be expected to either transfer or absorb significant quantities of moisture. This moisture transfer characteristic of the solid waste must be considered in the design of incinerators and projection of the load of individual refuse categories in the future. Table 4 shows the percent of moisture in refuse on an "as-discarded" and "as-fired" basis (Niessen et al. 1972, Table 6).

TABLE 3

ESTIMATED AVERAGE MUNICIPAL REFUSE COMPOSITION, 1970

(Weight Percent, As Discarded)

Category	Summer	Fall	Winter	Spring
Paper	31.0	39.0	42.2	36.5
Yard Wastes	27.1	6.2	0.4	14.4
Food Wastes	17.7	22.7	24.1	20.8
Glass	7.5	9.6	10.2	8.8
Metal	7.0	9.1	9.7	8.2
Wood	2.6	3.4	3.6	3.1
Textiles	1.8	2.5	2.7	2.2
Leather & Rubber	1.1	1.4	1.5	1.2
Plastics	1.1	1.2	1.4	1.1
Miscellaneous	<u>3.1</u>	<u>4.0</u>	<u>4.2</u>	<u>3.7</u>
Total	100.0	100.0	100.0	100.0

The calorific or heating value and fixed carbon contents of the solid waste play an important role in design of incinerator's heat recovery systems and air requirement for complete combustion of the refuse. Table 5 shows the heating value and fixed carbon contents of municipal refuse.

The overall refuse collected containing a yard waste percentage of 14.1 on an as-discarded basis (12.6 percent on an as-fired basis) showed the following characteristics:

* Heating Value	-	4,450 Btu/lb as fired (HHV)
* Percent Moisture	-	28.3
* Percent Ash	-	20.8
* Air Requirement	-	3.18 lb/lb refuse

TABLE 4

PERCENT MOISTURE IN REFUSE ON "AS-DISCARDED"
AND "AS-FIRED" BASES

Component	As-Fired	As-Discarded
Food Wastes	63.6	70.0
Yard Wastes	37.9	55.3
Miscellaneous	3.0	2.0
Glass	3.0	2.0
Metal	6.6	2.0
Paper	24.3	8.0
Plastics	13.8	2.0
Leather & Rubber	13.8	2.0
Textiles	23.8	10.0
Wood	15.4	15.0

Projection into the future (through the year 2000) of the per-capita waste loads and refuse compositions were estimated using the national indicators that were developed. These indicators take into account the national growth rates in the production of the commodities

comprising the major sources of each refuse component. The results are shown in Table 6 (Niessen et al 1972, Table 7).

TABLE 5
ESTIMATED HEATING VALUE AND FIXED CARBON
OF MUNICIPAL REFUSE CATEGORIES

Category	Fixed Carbon Percent (Dry Basis)	Heating Value, Btu/lb (Dry Basis)
Metal	0.5	740
Paper	11.3	7,930
Plastics	5.1	11,500
Leather & Rubber	6.4	10,175
Textiles	3.9	8,030
Wood	14.1	8,400
Food Wastes	5.3	8,540
Yard Wastes	19.3	7,300
Glass	0.4	65
Miscellaneous	7.5	3,500

TABLE 6

PROJECTED AVERAGE GENERATED REFUSE COMPOSITION
HEATING VALUE AND QUANTITY, 1970-2000

	1970	1975	1980	1990	2000
<u>Composition:</u>					
<u>(Weight %, As-Discarded)</u>					
Paper	37.4	39.2	40.1	43.4	48.0
Yard Wastes	13.9	13.3	12.9	12.3	11.9
Food Wastes	20.0	17.8	16.1	14.0	12.1
Glass	9.0	9.9	10.2	9.5	8.1
Metal	8.4	8.6	8.9	8.6	7.1
Wood	3.1	2.7	2.4	2.0	1.6
Textiles	2.2	2.3	2.3	2.7	3.1
Leather & Rubber	1.2	1.2	1.2	1.2	1.3
Plastics	1.4	2.1	3.0	3.9	4.7
Miscellaneous	3.4	3.0	2.7	2.4	2.1
<u>(Weight %, As-Burned)</u>					
Moisture	25.1	23.3	22.0	20.5	19.9
Volatile Carbon	19.6	20.1	20.6	21.8	23.4
Total Ash	22.7	23.4	23.9	22.8	20.1
Ash (excluding glass & metal)	6.5	6.2	6.1	6.0	6.0
<u>Relative Heating Value & Quantity:*</u>					
Heating Value (Btu/lb) as-fired	1.00	1.02	1.04	1.09	1.17
Heating Value (Btu/lb) dry basis	1.00	1.00	1.00	1.06	1.09
National Population	1.00	1.05	1.10	1.31	1.51
Per-Capita Refuse Generation (lb/person/day)	1.00	1.13	1.26	1.44	1.66
Per-Capita Refuse Heat Content (Btu/person/day)	1.00	1.15	1.31	1.57	1.94
Total Generated Refuse Quantity (lb)	1.00	1.19	1.38	1.89	2.51
Total Refuse Heat Content (Btu)	1.00	1.23	1.44	2.05	2.93

* Ratio relative to 1970 value.

III. LITERATURE REVIEW OF MODELS IN SOLID WASTE MANAGEMENT

General

The management of urban solid waste systems is among the most complex municipal or regional governmental tasks, principally because of the wide diversity of the components of solid wastes and the variety of systems in existence. Modeling is therefore frequently done on a specific basis, and the number of general models which can be used in different situations is relatively small.

There are a number of properties inherent in solid waste that compound the difficulties of decision making and modeling. One is the fact that the term solid waste refers to many varieties of materials. Some of these materials such as bulky white goods, bedsprings, demolition rubble, abandoned automobiles, etc., require different modes of handling.

There are wide differences in the methods of dealing with solid wastes among the municipalities, even between similar ones. Thus, models and techniques that are applicable in one locality may not be applicable in another locality because of the differences within the existing systems. It is observed that there is no unified view of the solid waste system. Therefore, no single approach to the problem exists.

Models in solid waste management are, in general, divided into

two major categories (Liebman 1974): models of long range policy decisions, and models of management decisions. Included in policy decision models are those related to national resource policy, e.g. the extent to which recycling and reclamation should play a part in solutions to solid waste problems. Models of management decision include: optimization models for planning the installation of fixed facilities used for transfer, treatment, and disposal, models dealing with the vehicles transporting the waste, and models which consider the scheduling of manpower. Liebman (1974) lists the various models in solid waste management, as shown in Table 7. For the purpose of this report, only the models dealing with fixed facilities will be reviewed.

Models Relating to Fixed Facilities

Problems related to fixed facilities may be solved by two very similar models. These are the selection of types of facilities to use for treatment (facility selection problems), and the selection of locations at which to install these facilities (site selection problems). The fundamental objective of site selection models are finding the optimal balance between costs of building and operating facilities and the costs of transporting material to and/or from these facilities.

Several investigators have attempted to apply operations research techniques to the problem of locating solid waste disposal facilities. Some of these models as reviewed by Helms and Clark (1971) are:

Wersan's Algorithm. - Wersan's approach to the problem is based on minimizing travel time between solid waste generation areas

TABLE 7

MODELS IN SOLID WASTE MANAGEMENT

Model/Decision Area	General Type	Important Characteristics
<u>WASTE:</u> Generation Prediction	Forecasting	Uses historical data to forecast amount of waste generated
Generation Prediction	Input-Output	Permits examination of impact of changes in one sector on waste stream in other sectors
<u>FIXED FACILITIES:</u> Site Selection	Integer programming	Selects sites for facilities from among specified alternatives; considers costs of transportation, construction, and operation
Capacity Expansion	Optimizing: integer or dynamic programming, heuristic	Usually neglects changes in land value, interest rates
Facility Operation	Queueing	Analysis number of loading docks, size of storage facilities
<u>VEHICLES:</u> Vehicle Replacement	Integer programming	Selects vehicles to be replaced
Single Vehicle Routing	Travelling salesman, truck dispatching	Requires specific collection points
Single Vehicle Routing	Chinese postman	Treats collection as continuous on streets

TABLE 7 (CONTINUED)

Model/Decision Area	General Type	Important Characteristics
Multiple Vehicle Routing	Heuristic	Simultaneously districts a large area into truckloads and routes individual vehicles
Multiple Vehicle Routing	Simulation (random walk)	Determines routes randomly; user selects best route found
MANPOWER: <u>Crew Assignment</u>	Non-linear programming, heuristic	Sequences vacation, time off, and overtime
Route Scheduling	Linear programming	Minimizes overtime and penalties for late or early services
OVERALL SYSTEM: <u>System Operation</u>	Simulation	Permits exploration of effects of policy and equipment change

and disposal sites (Wersan et al. 1963). The travel time is determined as the sum of the total time segments that take to travel in an L-shaped path between generation and disposal points. This model does not consider the fixed costs when different disposal alternatives are examined. Thus, it will not be effective in selecting disposal alternatives that require any capital investment.

Schultz's Algorithm. - Schultz's algorithm is based on minimizing the total weighted distance from generation to disposal points (Schultz 1967). Straight line distances are measured from the center of gravity of the generation area to the disposal site. The solution to this model begins by first selecting a random pattern of initial facility location. Second, the total area to be served is subdivided into compact service areas, each of which is associated with a facility. A solid waste generation area is assigned to a service area, such that the distance from its center of gravity to the facility is minimized. Third, a new pattern of facility location is tried. If no improvement can be made over the previous pattern, it is the optimal location pattern. Otherwise, the solution is repeated.

The capital or operating costs associated with different facility locations are not considered. In the case of transfer station locations, operating costs might be similar, but differences in location costs might cause the solution to be far from the minimum.

Baker's Algorithm. - Baker (1963) employs a trial and error approach to locating and assigning solid waste generation areas to disposal facilities. He uses a variable unit cost based on the utilization level of feasible alternative facilities. Facility utilization

is divided into four levels: 80% to 100%, 60% to 79%, 40% to 59% and 0% to 39%. Although Baker does not explicitly consider the fixed charge problem, he recognizes its existence by assigning a lower unit cost at high utilization levels.

The Baker technique compares alternatives, using the lowest cost per ton for each transfer station and final disposal combination. He assumes that the incinerators and compost plants are final disposal facilities. The total cost for each generation area is calculated using every possible disposal alternative, assuming a maximum capacity (80% to 100%). The alternative with the lowest cost for each area is then chosen.

The total solid waste generated by each area is checked against the assumed capacity for the disposal facility serving that area. If it is less than the assumed utilization level, the utilization is adjusted to actual level and the least cost calculation is repeated. If it is more than the assumed utilization level, solid waste source areas are removed one at a time until generation is equal or less than capacity. The source areas that have been removed are assigned to the next least cost alternative.

University of Louisville Approach. - Investigators at the University of Louisville (1968) used a linear programming model for locating landfills, incinerators, and transfer station facilities. The costs component of the model include those relating to operation of landfills, incinerators, transfer stations, and transportation between solid waste generation sources and disposal sites, between transfer stations or incinerators and disposal sites. Different alternatives

are formed by assigning various combinations of facilities to each source. Using linear programming procedures, the system is optimized and the minimum total cost is determined. The basic limitation of this approach is that it must assume linear cost functions, which makes its general use questionable.

A simple model for the site selection problem, with a rather unrealistic assumption of linear costs of facility capacity and linear transportation costs, may be formulated as:

Minimize:

$$\sum_i \sum_j (T_{ij} + D_j) X_{ij}$$

Subject to:

$$\sum_j X_{ij} = B_i \quad \text{for each source } i$$

Where: X_{ij} is the amount of waste shipped from source (collection area) i to site j .

T_{ij} is the cost, including capital, for each ton of waste to be shipped from source i to site j .

D_j is the operating cost, excluding capital, for each ton of waste which passes through an incinerator at site j .

B_i is the amount of waste generated at source i .

The model assumes a given set of potential sites for facilities, and a set of sources of known amounts of waste. The objective function is the total cost, including both transportation and facility costs, and the constraints require that the total amount of waste generated in each collection area be collected. The upper limits on the capacity

of the facility to be constructed at site j , B_j , may be presented by the addition of the constraint

$$\sum_i X_{ij} \leq B_j \quad \text{for each site } j$$

The problem may be solved by use of a standard transportation method. The model may also be expanded to include intermediate facilities such as transfer stations where waste is transferred from small collection vehicles to larger long-haul vehicles for transport to a distant treatment or disposal facility. Such a model is in the form of a transshipment problem which may also be solved by a special form of transportation method.

The limitation of the above models are that they neglect the initial cost of establishing a facility. For facilities with rather large initial capital cost, the unit cost of the facility decreases with the increase of its size. This results in it becoming more attractive to construct fewer large facilities. Thus, models of the above type normally overestimate the optimal number of facilities.

Fixed Charge Problem

In establishing a solid waste facility, be it a transfer station, incinerator, or landfill, an initial capital investment cost including interest for the cost of money is incurred. In such case, the total cost of the facility is the sum of the capital cost to build the facility and a variable operating cost depending on the utilization level of the facility. Such fixed charge problems may be presented graphically, as shown in Figure 2, and mathematically as:

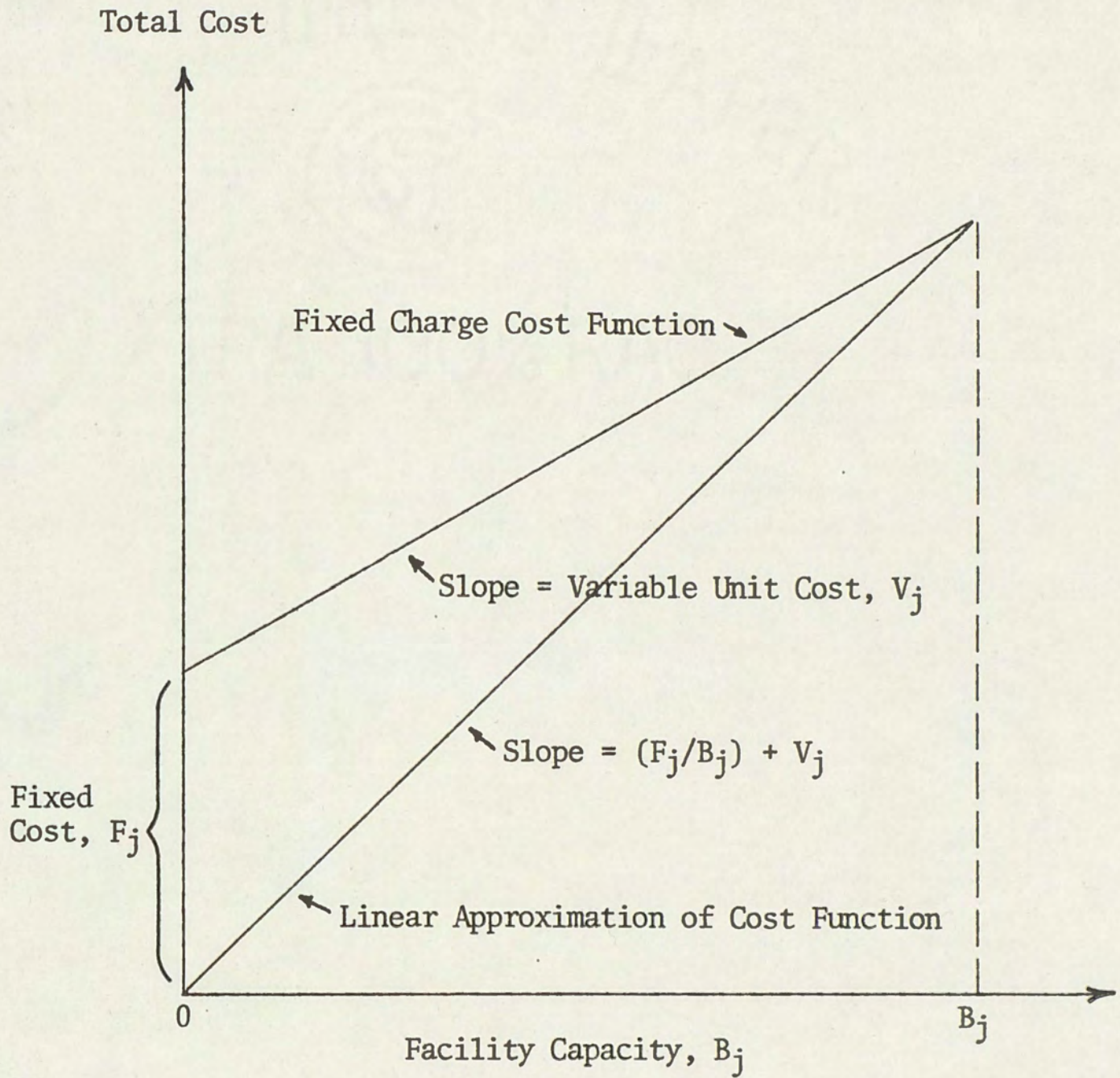


Fig. 2. Cost Function with Fixed Charge

$$g_j(B_j) = F_j + V_j B_j$$

in which $g_j(B_j)$ is the total cost function, F_j is the fixed cost in dollars, V_j is the variable cost in dollars per unit of capacity and is normally assumed to be linearly proportional to the capacity or utilization level, and B_j is the capacity of the facility. Figure 2 shows the total cost as a function of capacity utilization. The upper line with the slope equal to the variable cost V_j starts at fixed cost F_j for $B_j = 0$ and increases as level of utilization increases. The lower line with the slope equal to $(F_j/B_j) + V_j$ is the linear approximation of cost function and will be explained later in this section.

The function $g_j(B_j)$ is concave for $B_j \geq 0$. Minimization of an objective function that is concave yields an optimal solution at an extreme point of the convex set of feasible regions. The solution can, however, be a local optimum different from the global optimum. The presence of these local optima makes the solving of fixed charge problems difficult.

The fixed charge problem can be solved by introducing a zero-one variable, Y_j , into the total cost function such that

$$g_j(B_j) = V_j B_j + F_j Y_j$$

$$\text{Then} \quad \text{Minimize} \quad Z = \sum_{j=1}^n g_j(B_j) \quad B_j \geq 0$$

$$\begin{aligned} \text{Where:} \quad & \text{For } B_j = 0; \quad Y_j = 0, \quad \text{and} \quad g_j(B_j) = 0 \quad \text{and} \\ & \text{For } B_j > 0; \quad Y_j = 1, \quad \text{and} \quad g_j(B_j) > 0 \end{aligned}$$

There are a number of site and/or facility selection models that consider the fixed charge associated with each facility directly

by including a zero-one variable which indicates whether a facility is constructed or not.

The general mathematical form of such models is:

Minimize:

$$\sum_i \sum_j (T_{ij} + D_j) X_{ij} + \sum_j F_j Y_j$$

Subject to:

$$\sum_j X_{ij} = B_j \quad \text{for each source } i$$

$$B_j Y_j - \sum_i X_{ij} \geq 0$$

$$Y_j = 0, 1$$

where Y_j is equal to 1 if a facility is built at site j and zero otherwise. Other variables are as previously defined. The objective function now includes the fixed charge of a facility and is considered only if Y_j equals to 1, indicating that the facility is built. The second constraint requires that if a facility is built, the amount flowing into it may not exceed its capacity, while if it is not built there may be no flow into it.

This model may be further extended to be used to select among various types of facilities, or various capacities of the same type of facility at the same site. These facilities are treated as though they were at different sites. Such models include an additional constraint that ensures the construction of not more than one type of a facility or one size of the same type facility at the same site. For example, if an incinerator, a landfill, or a transfer station may be

built at a particular site, then by assigning $J = 2, 4$, and 7 , the new constraint is

$$Y_2 + Y_4 + Y_7 \leq 1$$

which prohibits building more than one of them. Similar constraints may be used to prevent any particular combination of facilities which, for any reason, is considered impossible or undesirable.

One of the methods that is used to solve the fixed charge problems is mixed integer programming. Several investigators have used branch-and-bound, cutting plane, heuristic or approximation techniques. A linear approximation of cost function is presented earlier in Figure 2. The approximation is arrived at by dividing the fixed charge F_j by facility capacity B_j and adding to the variable unit cost V_j . The approximation cost underestimates the true cost function except at two points where they are equivalent. These are when there is no flow through the facility, and when the flow equals the capacity.

Probably the most efficient technique designed to solve the fixed charge problem is a heuristic algorithm developed by Walker (1968, 1973), as reported by Helms and Clark (1971) and Liebman (1974). This is an adjacent extreme point algorithm which is computationally efficient in yielding optimal solution. The method is designed to handle any linear programming problem in which there is an initial fixed charge for any variable which becomes non-zero, as well as a linear charge as the variable increases in value. The solution technique is a modification of the simplex method for solving linear programming problems, which does not guarantee global optimality. However, computational experience with the Walker algorithm has demonstrated that it

almost always does find the optimum solution, and when it fails it still comes quite close in most cases.

The site or facility selection models reviewed in this section are time invariant models. They solve the problems at a particular time when the need of a solution is great. The overall problem of solid waste management is, in a broader sense, determination well in advance of when new facilities will be required and how much capacity should be provided at each time over some planning horizon. Such problems can also be investigated by means of models known as capacity expansion models.

Capacity Expansion Models

The purpose of a capacity expansion model is to examine the size and sites of future facilities, the time to build them, and the enlargement of the facilities that are currently operating. These models minimize the present value of all the future costs by applying interest for cost of money and discount factors. In developing these models, various assumptions have to be made. The assumptions include the length of planning horizon, whether the planning horizon is considered to be continuous or discrete, and the interval period if discrete. Capacity expansion models also require the knowledge of the future solid waste generation rate and the projected construction and operating cost of facilities. The difficulty of obtaining these data and requirement of various assumptions make the capacity expansion models very complex models. The complexity of these models has hampered their widespread use in the solid waste field.

One of the few capacity expansion models available is the one by Skelly (1968). The model is designed for planning of regional refuse disposal systems. The following is a description of this model as is reviewed by Helms and Clark (1971): Skelly has developed a model based on Walker's solution for the fixed charge problem. The model considers initial construction cost as well as variable operating cost for a facility. A discrete planning horizon of a five-year period is assumed. Most of the costs elements; population for each community; per capita of the waste generation of each community; and travel time from a community to a disposal site are assumed constant in any time period but variable among time periods. The model does not consider time variation in the cost of land or in the capital cost of facilities. These costs related to future facilities are those valued in the first time period. Thus, purchase of land in future time periods and stage development of incinerators and transfer stations cannot be considered with this approach.

A particularly extensive model which includes both initial site selection and capacity expansion is an optimization model presented by Esmaili (1972). This model uses an elaborate objective function to make an optimal selection of solid waste processing or disposal facilities, or both, among a potential number of such facilities for a given area over an extended period of time. The model includes both capital and operating costs of facilities, transport costs, and a discounting factor for facilities that are not used for the total period of their useful life. The capacity related costs of facilities, such as fixed capital costs and variable operating costs,

are determined empirically. Empirical relationships also are used to determine the transport distances between the waste generation sources and processing or disposal facilities and between the various facilities, as well as to relate the transport time to transport distance between any two plants.

The optimization procedure for solution to the model involves an eight-step process. These steps enumerate, in an orderly fashion, the possible configuration of allocation of waste generating sources to a combination of facilities in each time period. The consideration is given to a particular configuration only if it yields an improvement over the best configuration found so far.

The model does not allow for construction of overdesigned capacity facilities in anticipation of an increase in future waste generation. It is assumed that each facility would be expanded when needed. Usefulness of the information obtained from the output of this model is highly dependent on the accuracy of the numerous input data to the model and the reliability of the empirical relationships provided.

Another model comparable to that of Esmaili's was developed by Fuertes (1973). This model minimizes the total economic cost to operate and construct the entire solid waste disposal system over a planning horizon, given the initial system. The model is region-oriented and was tested for the solid waste disposal service in 39 cities and towns in the Boston Metropolitan area for the period from 1970 to 2000 (Fuertes et al., 1974).

In construction of solid waste facilities, such as incinerators, policy related economical questions are often considered. Such

questions may concern trade off between building large enough unloading facilities to shorten the trucks waiting time and expending less capital investment in expense of longer idle time for trucks. Another question may be choosing between facilities with large storage areas for continuous operation and facilities with smaller storage areas for normal daily operations. There are models that answer these and similar other questions. These models are not reviewed in this report.

IV. OPTIMIZATION MODEL

The various models reviewed in the last section reveal that application of modeling methodologies to solid waste management systems is fairly new. For this reason, a general trend as to applicability of certain models to various situations has not yet been established.

In most cases, the models have not yet been applied; in those few cases where models have been applied, either the results have not yet been implemented, or there is insufficient information to judge the final outcome. (Liebman 1974, p. 155)

Marks (Marks and Liebman 1970, 1971) has developed an optimization model which determines appropriate locations for transfer facilities where sources of waste and disposal sites are known. This model has been applied successfully to somewhat hypothetical studies made for solid waste systems in Baltimore. The objective function minimizes the capital and operating cost of the transfer station plus the transport costs. Capacity constraints are introduced to ensure that input to each transfer station equals its output, and disposal sites receive no more waste than their capacities. The model considers fixed charges related to each facility by including zero-one variables.

This model will be adapted and modified, to serve the purpose of this report, by extending it to also include the selection of locations of modular incinerators, in addition to selection of locations of transfer stations.

At this point, it is appropriate to briefly describe the

function of transfer stations as applied to the solid waste system encountered in this report. A transfer station is considered to be a facility where the solid waste from several relatively small vehicles is placed into one large vehicle before being hauled to a modular incinerator plant. A transfer station may also serve the function of sorting the solid waste by separating the white goods, and other bulky items such as construction rubble and bedsprings, and then compacting the remains to a smaller volume.

The distance between the center of a collection area and the incinerator facility which is to serve that area will determine the feasibility of including a transfer station in the transport system. Another criteria, in addition to the distance travelled, will be the time required for transport, especially in traffic-congested cities. An economic analysis of a break-even distance, beyond which inclusion of transfer stations becomes feasible, in a hypothetical case is shown in Figure 3. In this figure, the unit cost of dollars per ton of transport between collection point and incinerator plant, directly or through transfer station, is plotted against the distance between collection point and incinerator plant. The intersection of direct haul cost plot with that of using transfer stations is the break-even distance. For distances below this point, direct haul is more economical, while for distances beyond this point, transfer stations are more economical.

In developing the optimization model for locating the incinerator plants and transfer stations, the following assumptions are made: the collection area is divided into a set of i collection tracts, such

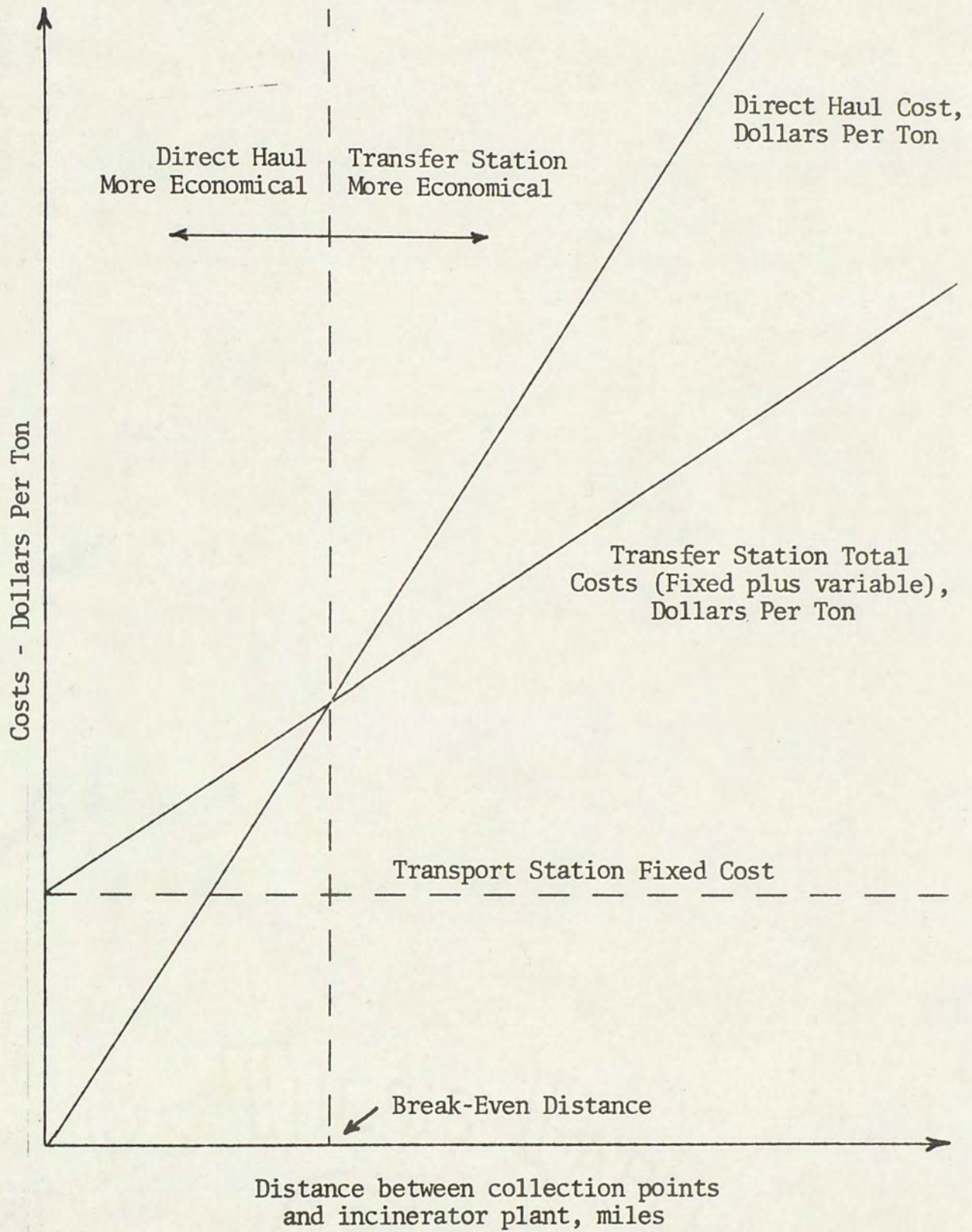
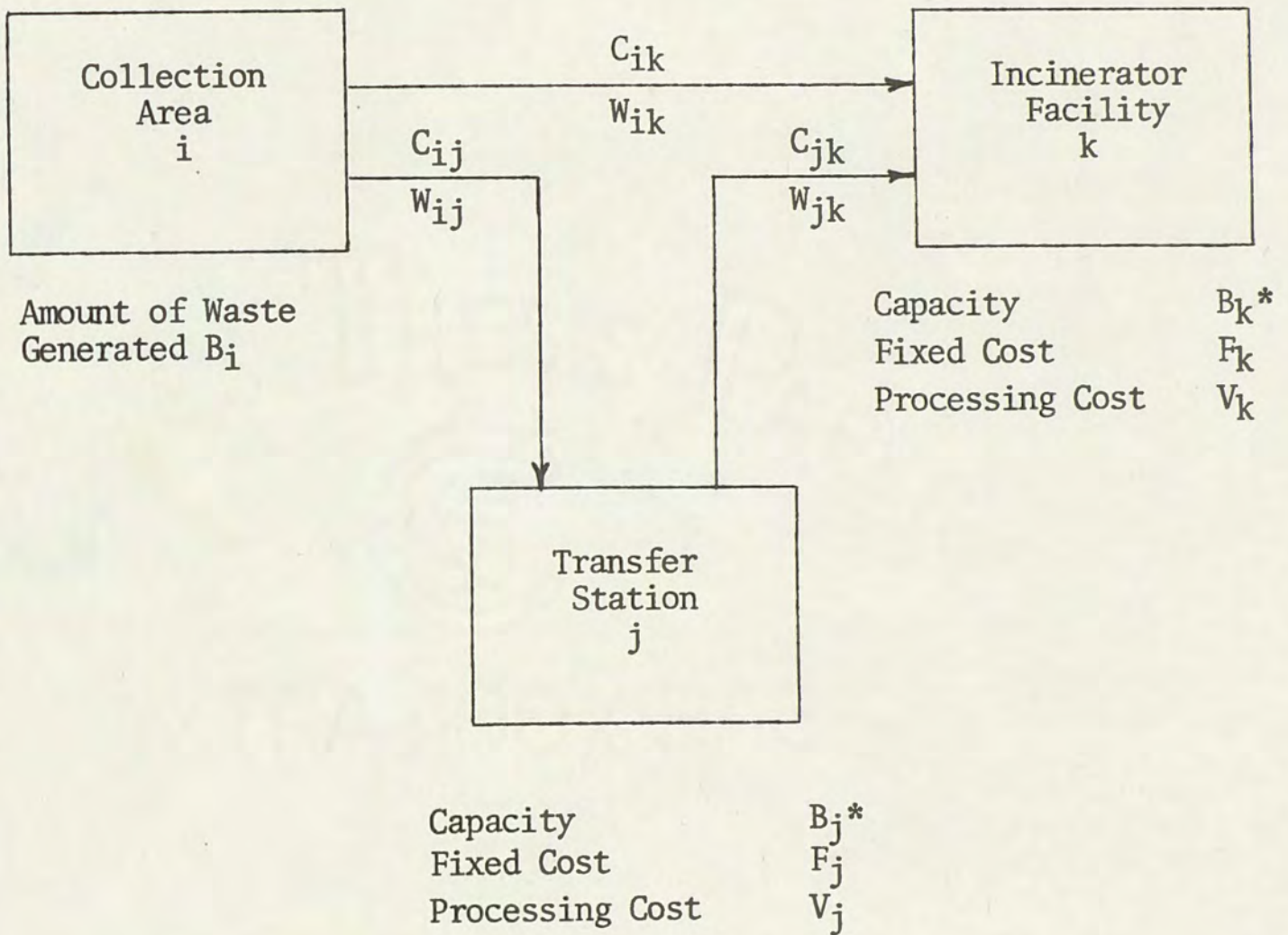


Fig. 3. Transfer Station Economic Analysis

as truckloads, with an amount of waste B_i generated at each tract i . There is a set of proposed transfer stations j and incinerator plants k , with associated fixed costs of F_j and F_k , and each with capacity B_j and B_k respectively. Each transfer station has a unit processing cost V_j , and each incinerator plant has a unit processing cost V_k . Figure 4 shows the flow of solid waste in the proposed system with associated costs and amount of waste transferred between each facility.



* B_j and B_k are the upper limit capacities of transfer stations and incinerator plants respectively.

Fig. 4. Flow of Solid Waste in the Proposed System

The mathematical statement of the model is:

Minimize:

$$\begin{aligned} & \sum_j F_j X_j + \sum_i \sum_j C_{ij} W_{ij} + \sum_k F_k Y_k \\ & + \sum_j \sum_k C_{jk} W_{jk} + \sum_i \sum_k C_{ik} W_{ik} \end{aligned} \quad (1)$$

Subject to:

$$\sum_j W_{ij} + \sum_k W_{ik} = B_i \quad \text{for each tract } i \quad (2)$$

$$\sum_i W_{ij} = \sum_k W_{jk} \quad \text{for each transfer site } j \quad (3)$$

$$\sum_i W_{ij} - B_j X_j \leq 0 \quad \text{for each transfer site } j \quad (4)$$

$$\sum_i W_{ik} + \sum_j W_{jk} - B_k Y_k \leq 0 \quad \text{for each incinerator plant } k \quad (5)$$

$$\sum Y_k \geq 1 \quad \text{for each system} \quad (6)$$

$$X_j = 0, 1 \quad \text{for each transfer site } j \quad (7)$$

$$Y_k = 0, 1 \quad \text{for each incinerator plant } k \quad (8)$$

$$W_{ij}, W_{jk}, W_{ik} = \text{non-negative integers} \quad (9)$$

Where: C_{ij} = cost of transporting a unit of waste from track i to transfer station j , including processing cost at transfer station j , (V_j)

C_{jk} = cost of transporting a unit of waste from transfer station j to incinerator plant k , including processing cost at incinerator plant k , (V_k)

C_{ik} = cost of transporting a unit of waste from tract i to incinerator plant k , including processing cost at incinerator plant k , (V_k)

W_{ij} = amount of waste transported from tract i to transfer station j (in truckloads)

W_{jk} = amount of waste transported from transfer station j to incinerator plant k (in trailer loads)

W_{ik} = amount of waste transported from tract i to incinerator plant k (in truckloads)

X_j = 1 if the j th transfer station is built, and zero otherwise

Y_k = 1 if the k th incinerator plant is built, and zero otherwise

The terms in the objective function minimize the fixed costs of transfer stations which are built, transport costs from collection tracts to transfer stations and processing costs at transfer stations, fixed costs of incinerators which are built, transport costs from transfer stations to incinerator plants and processing costs at incinerator plants, and transport costs from collection tracts to incinerator plants and processing costs at incinerator plants respectively. Equation (2) requires that all waste generated at each tract be collected. Equation (3) ensures that input to each transfer station equals its output. Equations (4) and (5) specify that if a transfer station or incinerator plant, respectively, is not built it can handle no waste, while if it is built it can handle no more than its capacity. Equation (6) ensures construction of at least one incinerator plant. Equations (7) and (8) require that a transfer station or incinerator plant, respectively, be built or not-built. Equation (9) prevents back-haul between facilities and also eliminates partially full trucks

or trailers.

Additional constraints may be placed in the model without significantly affecting the solution technique. The two most important of these are (a) a budget constraint, which limits either the amount of capital costs for construction of facilities or the number of facilities, and (b) a constraint which considers construction of different sizes of a facility at a location.

Because the model is a mixed-integer linear programming problem, a form of branch-and-bound method is proposed for its solution. This method was applied to Marks' model in the Baltimore study, using a network flow algorithm for solving the individual branch problem.

Cases with 40 collection areas, 7 potential transfer facilities, and 2 disposal sites were solved on an IBM 7094 computer in approximately 45 seconds.
(Liebman 1974, p. 156)

Several runs have been made of the Marks' model in the above study. The first run was to verify that the data used were without error. In this run, no transfer stations were permitted and the model was simply used to calculate weekly collection costs. The result gave a cost of \$16,600 per week, using two times per week collection. This was four percent lower than estimated actual cost, thus indicating that the data were accurate. Few runs were made to explore the potential savings associated with transfer stations. The results indicated a saving of \$700 and \$900 per week for transfer stations of 600 tons per day and 900 tons per day capacities respectively. Additional runs were also made for three times per week collection and for increases

in waste generation rate ranging from 10 percent to 60 percent, all showed the same stability in selecting the identical site alternative. The model was also tested for possible effects of errors in estimating costs or other data by varying transport costs, collection rates, etc., these also demonstrated remarkable stability. Transfer stations remained (marginally) economical until the facility fixed cost almost doubled; and the same site was chosen with almost all combinations of data (Liebman 1974, p. 157).

Marks' model, however, assumes a set of known disposal (landfills) facilities whose sites do not have to be selected. The model developed in this report assumes both a set of transfer stations and a set of incinerator plants whose sites are to be selected. These assumptions may make the model more complicated. No attempt will be made to apply this model to any hypothetical or actual data. Therefore, its computational difficulties need further study.

V. SUMMARY AND CONCLUSIONS

Sanitary landfill has been a common disposal method used by municipalities. The unavailability of land, for use in landfills, grows as municipalities grow in size. This and stringent governmental regulations requiring resource recovery has added to the problems of the municipal solid waste managers who have to seek alternative solutions for the disposal of waste. One such alternative is energy recovery incinerators, particularly the modular incinerators.

Almost all large scale incinerators operate on an excess air principle in the primary chamber to control the heat in the emitted gas stream. This increased volume of air adds to the problem of air pollution, requiring an expensive and rather complicated pollution control devices (Hofmann et al., 1976). Large scale incinerators also require large quantities of waste, which means long hauling of waste resulting in an expensive transportation cost. On the other hand, the modular or small incinerators can be located near the waste generation sources to minimize the transportation cost. By utilizing controlled air designs, and by using auxiliary fuel to burn off particulate emission, they are able to meet EPA's air pollution control recommendations. The design of modular incinerators provides for energy recovery by including facilities for generation of steam (Pearson and Butner, 1975). Another important feature of these small units is that they provide flexibility for expansion as the city expands its waste

generation. With these points in mind, it is, therefore, recommended that the municipal solid waste managers consider use of modular incinerators as an alternative solution to their problems.

To provide the municipal solid waste manager a tool that can help him to optimally locate the modular incinerators, and transfer stations when feasible, an optimization model has been developed as was the objective of this report.

The model developed was adapted from presently available models in the solid waste management, and was modified to suit the purpose of this report. The model that was chosen for development was applicable to locating the transfer stations between the waste generation points and disposal facilities at known locations. This has been modified to optimally locate both a set of modular incinerator plants and transfer stations between these plants and the waste generation sources in a municipal system. The decision criteria of the modified model was developed in terms of minimum total costs of the system. The optimization model minimizes the sum of the costs of transport of waste and the operating costs of facilities, including fixed charge costs of constructing the facilities. The model, however, is not applicable to long-range planning problems. Due to flexibility of the modular incinerators, it is assumed that as the need arises, these units can either be added to existing plants, or new plants be built.

In developing the model, no landfill facilities were included in the system. Thus, the cost obtained by the model does not include either the transport costs from incinerators to landfill sites or the operating costs of landfill. Landfill facilities were left out of the

system due to the fact that incinerators achieve a weight reduction of about 75 percent, and a volume reduction of about 94 percent (Hofmann et al., 1976). The transfer cost of residues from incinerators to landfill sites is insignificant compared to the total costs of the system. In most cases, residues may be used in highway constructions as roadbeds (Pearson and Butner, 1975), and also in reclamation of lands in low-land areas, as it is presently practiced in an Orlando, Florida incinerator plant site (observation by the writer).

A branch-and-bound algorithm is proposed for obtaining the solution to the model. The computability of the model using the proposed algorithm has not been tested, however, and requires further research.

This model, as any other model in the solid waste system, cannot provide solution to the manager's problems. It, at best, can provide him with the economic profile of alternatives which he can use as a tool in decision making.

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