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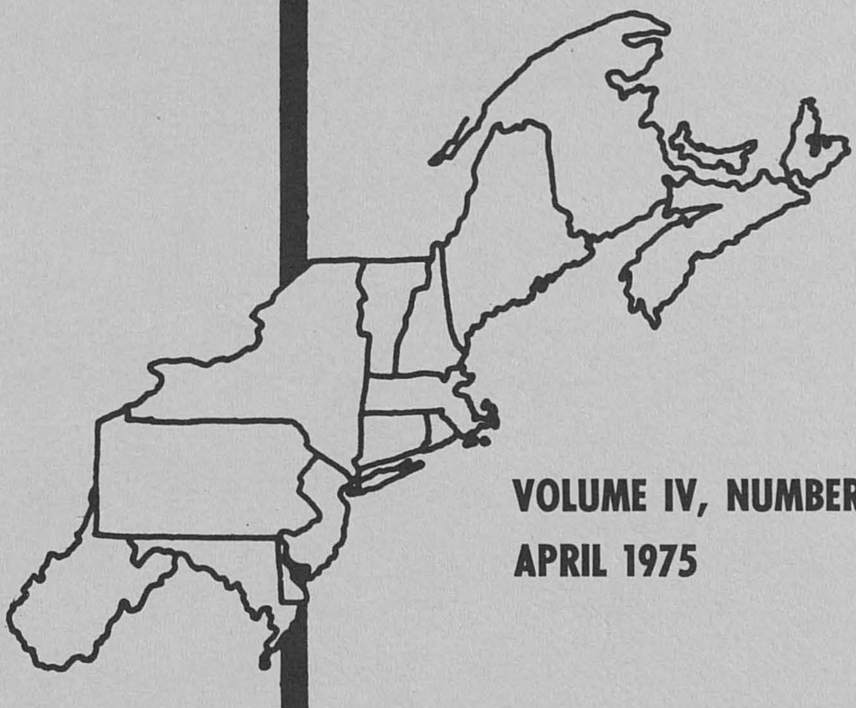

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AN APPLICATION OF THE TRANSHIPMENT MODEL IN PLANNING REGIONAL SOLID WASTE DISPOSAL SYSTEMS[1/]

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I. Introduction

An important component of the current interests in environmental problems concerns solid waste. Not only has public interest in solid waste disposal been substantial, but legislators have restricted ways by which solid wastes may be disposed. New Hampshire's State Legislature, for example, has passed a law requiring municipalities to cease all open burning by 1975 [6].

As solid waste disposal codes become more stringent, legally acceptable methods will involve higher costs. A possible way to reduce solid waste disposal cost is to take advantage of any economies associated with processing large quantities of waste. Such economies of scale apparently exist. One study reports that to process 400 tons per day would cost $10 per ton, while processing 1,200 tons would cost $4 [1]. The obstacle to the enjoyment of such economies is that many municipalities do not produce enough waste to justify high capacity (low unit cost) disposal plants.

Municipalities might circumvent this obstacle by forming a consolidated waste disposal district. With the total wastes produced in such a district, it may become economically justifiable to invest in high capacity disposal plants. If such a solution is pursued, the problem becomes one of determining the optimum (least cost) sizes and locations of disposal plants in the district. This paper suggests a solution.

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II. Procedure

A. Assumptions Underlying the Analysis

We are assuming waste disposal districts consist of municipalities in which the quantity of waste produced is known. It is further assumed that the collection of wastes is not part of the problem considered in this paper. More specifically, we assume that wastes produced within any municipality are assembled at some central point. Each municipality can either transport their centrally assembled wastes directly to an incinerator or to a transfer site where waste is compacted and then it is hauled by large tractor-trailer trucks to incinerators. In the most general statement of the problem, it is assumed that no incinerators or transfer compaction sites currently exist in the region; and size, as well as location, of these "processing plants" must be determined.

B. Mathematical Model

The suggested procedure is based on the linear programming transhipment model [3, 4]. The problem may be stated mathematically as:

$$\text{(1)} \quad \text{Minimize } TC = \sum_{i=1}^{M} \sum_{j=1}^{K} (T_{ij}^{C} + P_{j}^{C})X_{ij} + \sum_{i=1}^{M} \sum_{j=K+1}^{W} (T_{ij}^{C} + P_{j}^{I})X_{ij} + \sum_{i=M+1}^{V} \sum_{j=K+1}^{W} (T_{ij}^{H} + P_{j}^{I})X_{ij}$$

Subject to:

$$\text{(2)} \quad \sum_{j=1}^{W} X_{ij} = S_{i} \qquad \text{for } i = 1, 2, \ldots, V$$

$$\text{(3)} \quad \sum_{i=1}^{V} X_{ij} = D_{j} \qquad \text{for } j = 1, 2, \ldots, W$$

$$\text{(4)} \quad \sum_{i=1}^{V} S_{i} = \sum_{j=1}^{W} D_{j}$$

(5) $X_{ij} \geq 0$ for $i = 1, 2, \ldots, V$

$j = 1, 2, \ldots, W$

where, M = number of waste producing municipalities in the region

K = number of potential transfer compaction sites

N = number of potential incineration (processing) sites

V = M+K

W = N+K

TC = total cost of transporting and processing wastes produced in region i, $i = 1, 2, \ldots, M$

T^C_{ij} = cost of transporting one ton of waste from producing municipality i to either the j^{th} compaction site ($j = 1, 2, \ldots, K$) or the j^{th} incineration site ($j = K + 1, \ldots, W$)

T^H_{ij} = cost of transporting one ton of waste from the i^{th} compaction site ($i = M + 1, \ldots, V$) to the j^{th} incinerator ($j = K + 1, \ldots, W$)

P^C_j = cost of compacting one ton of waste at the j^{th} compaction site, $j = 1, 2, \ldots, K$

P^I_j = cost of incinerating one ton of waste at the j^{th} incinerator, $j = K + 1, \ldots, W$

S_i = quantity of waste supplied by producing municipality i, $i = 1, 2, \ldots, M$; or, quantity of waste supplied by transfer compaction site, $i = M + 1, M + 2, \ldots, V$

D_j = quantity of waste demanded (processed) by the j^{th} transfer compaction site, $j = 1, 2, \ldots, K$; or, quantity demanded (processed) by the j^{th} incinerator, $j = K + 1, K + 2, \ldots, W$

X_{ij} = quantity of waste shipped from the i^{th} producing municipality to the j^{th} compaction transfer site, for $i = 1, 2, \ldots, M$ and $j = 1, 2, \ldots, K$; or, quantity of waste shipped from the i^{th} producing municipality to the j^{th} incinerator for $i = 1, 2, \ldots, M$ and $J = K + 1, \ldots, W$; or, quantity of waste shipped from the i^{th} compaction transfer site to the j^{th} incinerator, for $i = M + 1, \ldots, V$ and $j = K + 1, \ldots, W$

C. Schematic Presentation of the Model

A specific case of this model is presented in Figure 1. Here, the number of waste producing municipalities (M) is three; the number of potential compaction sites (K) is three; and, the number of potential incineration sites (N) is also three.

The model contains a cost matrix with four quadrants. Two types of processing operations are considered - incineration and compaction, where incineration plays the role of final demand. The northwest quadrant (A) contains both the unit cost of transporting wastes from each producing municipality to each compaction site and the unit cost of compaction. The northeast quadrant (B) contains both the unit cost of transporting wastes from each producing municipality to each incineration site and the unit incineration cost. Note that in the Hurt-Tramel [3] formulation of the problem, this quadrant is excluded from the analysis with high unit costs. In this problem, this quadrant is a relevant component of total costs because the option of shipping directly to incinerators is feasible.

Figure 1
Schematic View of Model[a/]

		Transfer Compaction Sites			Incinerator Sites			S_i
		1	2	3	4	5	6	
Producing Municipalities	1	(A)			(B)			15
	2		T^C_{ij}	$+ P^C_j$		T^C_{ij}	$+ P^I_j$	8
	3							7
Transfer Compaction Sites	4	(C) 0	*	*	(D)			30
	5	*	0	*		T^H_{ij}	$+ P^I_j$	30
	6	*	*	0				30
Dummy Municipality	7	*	*	*	*	*	*	60
D_j		30	30	30	30	30	30	

a/ Asterisks (*) indicate high costs.

The southwest quadrant (D) consists of zeros along the main diagonal and high costs off the diagonal. This quadrant indicates the excess capacity of the compaction sites. Finally, the southeast quadrant (D) contains both the unit cost of hauling compacted wastes from each compaction site to each incinerator and the unit cost of incineration.

Another deviation of this model from that of Hurt and Tramel [3] is the addition of a "dummy municipality" as the last row in the cost matrix. This row contains high and uniform unit costs and serves to indicate the excess capacity of the incinerators.

The S_i and D_j components of the model are arbitrarily (but consistently) recorded in Figure 1. Note that each compaction and incineration site is assigned a capacity sufficient to process all wastes produced in the region (say 30 tons). Also the "S_i" component for the "dummy municipality" serves to balance supplies and demands and thus satisfies the restriction depicted by equation (4) above.

D. Iterative Procedure for Final Solution

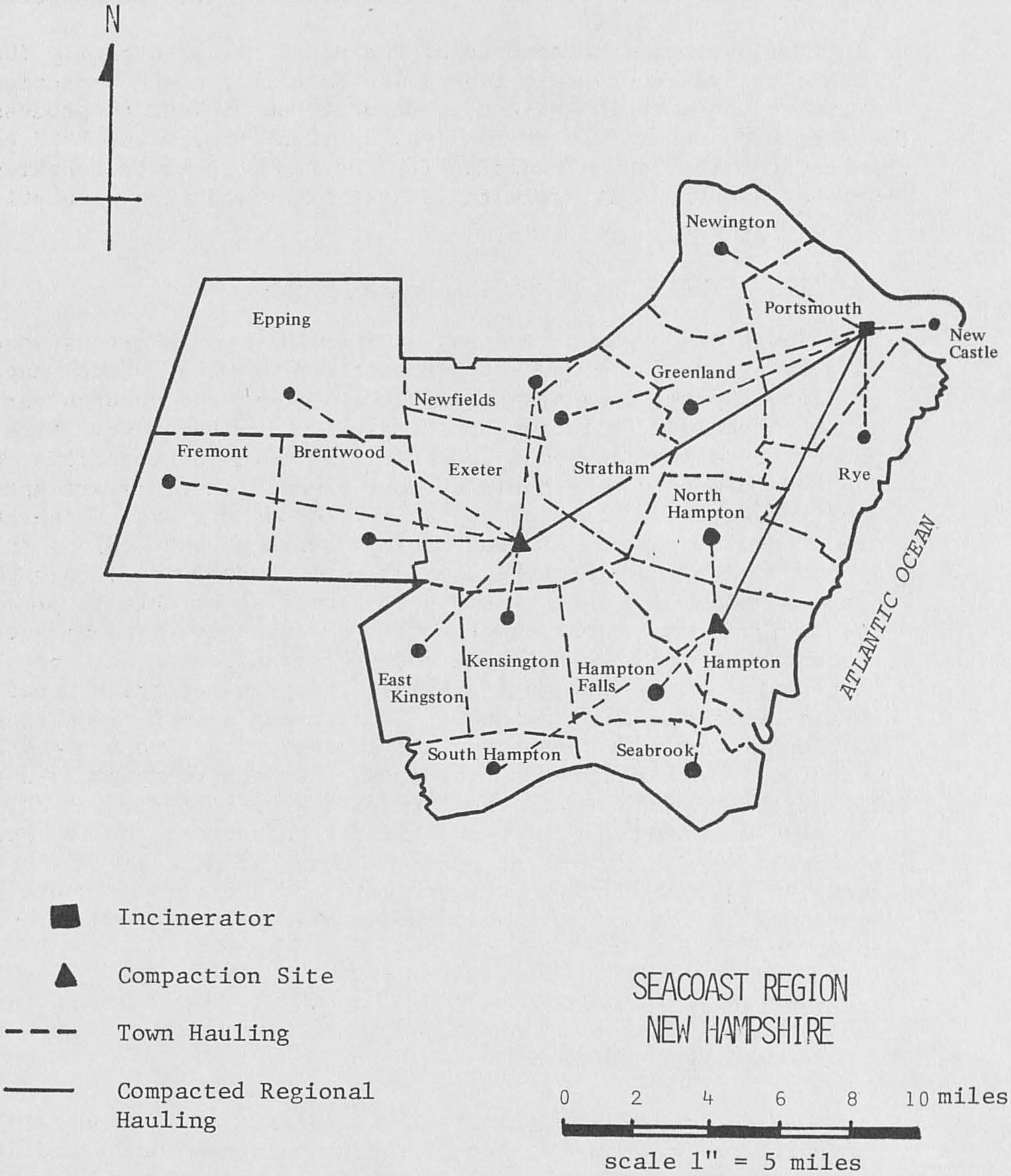
The average compaction and incineration costs are assumed to be a function of the quantity of wastes processed. Since capacity or size of processing plants and location are the unknown variables to be determined, solution of the problem is iterative. First, K potential compaction and N potential incineration locations, one in each municipality, and their average production costs are specified. At first we assume that all potential compactors and incinerators are at their maximum size and minimum average cost. Since this type of model might best be used as a planning device, each potential compactor and incinerator are assumed to be able to process the region's entire output of waste. Using these minimum average processing costs, the relevant costs of transportation, and the waste produced in each municipality, the transportation model is solved by conventional methods. Then, using a long-run average cost curve for both compaction and incineration, average costs are made consistent with the allocations of wastes to compactors and incinerators specified in the foregoing run. After these adjustments, the problem is rerun and further adjustments of the average compacting and incinerating costs are made if necessary. The solution is complete when the prespecified average costs are consistent with the transportation model allocations of the previous solution.

III. Application of the Model

A. Region Studied

The region studied (Figure 2) is located in southeastern New Hampshire and consists of one of the planning regions specified by the Governor's Committee on Regional Planning in New Hampshire [5]. All 18 municipalities in the region are located in Rockingham County - which is the most rapidly growing county in the State as witnessed by a 40 percent population increase over the 1960-1970 period. The most populous municipality in the region is Portsmouth-population in 1970 about 26,000. Other municipalities in the

Figure 2. Region Studied and Final Shipment Pattern



region are smaller with 11 having resident populations less than 2,000. The total area of the region is approximately 250 square miles, with the furthest distance between any two points being about 25 miles.

B. Data Used in the Analysis

Data required for the analysis included solid waste production estimates for each municipality, cost of transporting solid wastes both in compacted and non-compacted forms, and compaction and incineration costs.

(1) Solid Waste Production

Total solid waste produced within each municipality was estimated on the basis of an average refuse production per capita per day of three pounds. Nationally, refuse per capita per day ranged from three to five pounds. Conferences with officials in the study region indicated that the lower end of the range was more applicable to the region due to the absence of large quantities of industrial wastes. The average was then multiplied by the number of residents in the municipality to yield total refuse production for each municipality. Since wastes would probably be processed on a weekly basis, the resulting estimates were multiplied by 7 to reflect weekly refuse production. These figures constitue the S_i's for the producing municipalities in the model presented above.

(2) Transportation Costs

Costs of transporting wastes from any municipality to either a transfer compaction site or to an incinerator were taken from a study of Baltimore [2]. This study reported costs as a function of distance travelled, travel speed, number of laborers excluding driver, and cost per hour of vehicle and driver. For this study, however, costs were estimated for "average conditions" at $0.203 per mile per ton. Costs of transporting (hauling) compacted wastes to an incinerator were based on a Vermont Solid Waste Study [7]. Again, assuming average conditions, the estimated cost per mile per ton for hauling type vehicles was $0.07.

(3) Processing Costs

The average cost functions for compaction and incineration were estimated by least squares from published data on average cost per ton and tons processed.2/ The average cost function

2/ Curves derived in this fashion are not long-run average cost curves since the latter are envelope curves. For the purpose of this paper, errors resulting from this type of misspecification appear insignificant.

for compaction was derived from data contained in a Vermont study [7]:

$$AC_c = 54.05X_c^{-0.95}$$

where, AC_c = cost of compaction per ton

X_c = quantity of waste compacted in tons

The regression coefficient was significant at the 1 percent level and the coefficient of determination (R^2) was 0.96. The average cost function for incineration was derived from stack-type incinerator data published by the Bureau of Solid Waste Management [1].

$$AC_I = 162.47X_I^{-0.49}$$

where, AC_I = cost of incineration per ton

X_I = quantity of waste incinerated in tons

The regression coefficient (exponent) was significant at the 5 percent level and the coefficient of determination (R^2) was 0.42. In both equations, the coefficients to quantity processed were statistically significant. However, in the incineration equation, only 42 percent of the variation in average costs (incineration) was explained by regression. This suggests that variables other than quantity incinerated are important determinants of incineration costs.

C. Empirical Results

Applying the model to the 18 municipality region resulted in a final solution in 5 iterations (approximately 10 minutes on a IBM 360-50). Over a one week period, 609 tons of solid wastes need to be processed. Incinerator capacities were initially assumed to equal the region's total waste production. Compactor capacities were initially assumed to equal one-half of the region's production. A smaller maximum capacity could have been specified since no compaction site was used to capacity.

The final shipment pattern specified by the model contained two transfer-compaction sites, Exeter and Hampton, and a single incinerator in Portsmouth (Table 1 and Figure 2). Sizes specified for the compactors were 148 and 145 tons for Exeter and Hampton, respectively. The size of the single incinerator met total regional processing requirements of 609 tons.

Table 1
Optimal Regional Shipment Pattern

Municipality	Solid Waste to be Disposed (Tons)	Optimal Shipments (Tons)		
		Compaction Sites		Incinerator
		Exeter	Hampton	Portsmouth
Epping	21	21		
Fremont	9	9		
Brentwood	13	13		
Exeter	80	80		(148)[a/]
Newfields	8	8		
Stratham	14			14
E. Kingston	8	8		
Kensington	9	9		
S. Hampton	6		6	
Seabrook	27		27	
Hampton Falls	11		11	
Hampton	72		72	(145)[a/]
N. Hampton	29		29	
Greenland	16			16
Rye	37			37
Portsmouth	234			234
Newington	6			6
Newcastle	9			9
TOTAL	609	148	145	609

a/ Compacted wastes shipped from compaction sites.

Total regional costs for processing the 609 tons per week was $4,870, or about $8 per ton. Since the study region does not contain an existing incinerator system, no meaningful cost comparison can be made.

VI. Conclusion

This paper suggests the use of the linear programming transhipment model as a tool in planning regional solid waste disposal systems. This model was applied to a simplified region and problem. More specifically, a system of intermediate compaction sites and incinerators was considered. We note, however, that this particular system of solid waste disposal was chosen to develop and expose the model. Hopefully, other methods of waste disposal, such as land fills, may be considered by the model presented above. Further, when sufficient information regarding the costs and techniques of recycling becomes available, this disposal method could be integrated into the model. Future research efforts will expand the model by including alternative methods of waste disposal simultaneously.

In a more realistic application of the technique, the following is offered. First, rather than using the municipalities as the basic elements in the region, a system of grids (say, 1 square mile in area) might be superimposed on the region. Resident population within each grid would have to be determined and distances between grid centers could be used as travel distances. Such a system of grids would better account for the distribution of solid wastes over the region. Also, it would involve more accurate estimates of distances travelled. Such a system would likewise permit more than one compaction site and incinerator per municipality. Second, rather than relying on a statistically determined average cost function, the synthesis of a cost function from engineering-type data is a more precise measure of this essential cost component. More precision in obtaining transportation cost estimates is also desired. The importance of precise cost components cannot be overemphasized since the reliability of locations and sizes specified by the model depends solely on cost comparisons. The dubious nature of the data used in this paper is readily admitted. However, the purpose of this paper has been more demonstrative rather than problem solving.

In conclusion, we are optimistic as to the use of this model in assisting the planning of regional solid waste disposal systems. The type of data require appear readily available and the time and expense of running the model is reasonable. Furthermore, if used as the first step in planning, it is entirely feasible to work with projected future populations and waste production rather than current estimates.

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