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## Abstract

Most of the United States have laws mandating the recycling of municipal solid waste (MSW). In order to comply, municipalities recycle quotas of materials, without regard to fluctuating prices. An inventory system is proposed that allows municipalities to be sensitive to materials prices as they recycle in accordance with state mandates. A dynamic model is developed; it uses historical secondary material prices as exogenous inputs to minimize the net present value of MSW recycling system cost. The model provides a cost-effective method for municipalities to achieve their MSW recycling targets. The savings is approximately $1.43 per ton of MSW generated based on total MSW management costs of $13.5 per ton. The model also allows one to investigate the effectiveness of various strategies for increasing the recycling rate. These strategies include: reducing the transportation cost for recyclables, supporting the market price of selected secondary materials, and landfill bans on selected materials. This model may also be used to investigate the effect of market price changes on the portfolio of materials held in inventory for recycling.

**Key Words:** Municipal Solid Waste, Recycling, Inventory, Optimization

**JEL Classification Numbers:** Q2

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## 1. Introduction

Most of the United States have laws mandating the recycling of municipal solid waste (MSW). In order to comply, municipalities recycle quotas of materials, without regard to fluctuating prices. The prices for all recycled materials tend to track fluctuations in overall demand for manufactured goods. Thus, the prices of the recycled materials can be very volatile. In current practice, recyclers at the municipal level do not hold the materials they collect for a long period of time. Instead, they sell their collected and sorted stock of recyclable material to dealers at current market prices. This practice prevents municipalities from maximizing the revenues from the sale of recyclable materials if they sell only at the highest market price. If municipalities could hold their stock of recyclables in inventory and sell each component only at its maximum market price in a given operating cycle, then the municipality could maximize its revenue from the sale of recyclables. Figure 1 illustrates this point.

In Figure 1, the supply of a recyclable material is infinitely inelastic and is represented by the curve S. This represents existing recycling practice. For the operating period under consideration, a municipality releases $q_1$ tons of material for sale at price $p_1$, $(q_2 - q_1)$ tons at price $p_2$, and $(q_3 - q_2)$ tons of material at price $p_3$. In the proposed system with an inventory of material, the municipality is able to hold all material for sale until the price rises to $p_3$. Let $R_1$

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represent the revenue earned under the existing recycling practice and $R_2$ represent the revenue earned under the proposed inventory system. Then:

$$\begin{aligned}
&R_1 = p_1q_1 + p_2q_2 + p_3q_3 - p_2q_1 - p_3q_2 \\
&R_2 = p_3q_3 \\
&R_2 - R_1 = p_2q_1 + p_3q_2 - p_1q_1 - p_2q_2 \\
&R_2 - R_1 > 0 \\
&R_2 > R_1
\end{aligned}$$

Managing revenue fluctuations can make or break a recycling program. Usually, negotiating long-term contracts that feature price floors or other revenue/risk sharing agreements, and broadening markets by developing local manufacturing demand for recycled feedstock, are used to moderate revenue peaks and valleys. The proposed inventory system gives municipalities an additional tool for controlling the revenue from their recycling operations.

The inventory concept is simple. Municipalities build warehouses to store their sorted recyclable materials. Based on the capacity of these warehouses and the predicted prices of materials during their operating cycle, the municipalities hold a portfolio of recyclables composed of different quantities of each type of material they recycle. They release these materials at their optimum price within the operating cycle, given their inventory capacity. Over the long-term planning horizon for evaluating the investment in warehouses and their operating and maintenance (O&M) cost, the net present value of the investment must be less than or equal to savings to the municipal recycling program. These savings are derived from larger revenues earned from the price advantage realized through inventory-based sale of its stock of recyclables.

The inventory method poses two major concerns for municipalities. First is the required capital investment in the warehouses. Second is the uncertainty about the future secondary materials market prices. This paper directly addresses the first of these concerns. Using historical data on secondary materials prices, we demonstrate that the proposed inventory system can significantly reduce MSW recycling cost to municipalities over a three-year planning horizon. A model to support decision making on the composition of the portfolio of recyclables and the time to release different materials for sale is being developed.

Integrated waste management establishes a hierarchy for municipal solid waste management that places a greater preference on waste reduction, reuse and recycling, than on landfilling and incineration (EPA 1989). Optimization models can help municipalities select the appropriate mix of technologies and recycling strategies for managing their MSW within the integrated waste management framework. The available optimization models include linear programming (LP), mixed-integer linear programming (MILP), dynamic programming (DP), and multi-objective programming (MOP) models. Lund (1990) developed an LP approach for optimal material recycling and landfill utilization. Baetz and Neebe (1994) developed a mixed-integer linear programming (MILP) model that is capable of determining optimal recycling program development levels for individual recyclable materials within an integrated waste management system. Chang et al. (1996) developed an MILP model, which combined environmental impacts, such as air pollution, leachate impacts, and traffic congestion into a location/allocation model for MSW system analysis. Baetz (1990) applied a DP model to determine the optimal capacity expansion pattern for waste-to-energy and landfill facilities. Perlack and Willis (1985) used a multi-objective programming model for the planning of a sludge disposal system.

Other researchers have used the simulation approach to study the effectiveness of various recycling policies. For example, Palmer et al. (1997) developed a simulation model to study three price-based policies, namely deposit/refunds, advance disposal fees and recycling subsidies, for solid waste reduction. Their results indicate that the deposit/refund is the least costly of the policies. In this paper, we develop a nonlinear programming model to minimize the net present value of costs in an MSW system that incorporates a warehouse for holding its stock of recyclable materials in inventory. This model allows decision makers to develop an optimal recycling strategy to maximize revenue when material market prices are unsteady and are given exogenously. The model developed in this paper adds the new concept of an inventory warehouse to the recycling literature and expands the list of options available to municipalities seeking to control cost in their recycling operations. Municipalities may also employ this model to aid in decisions on warehouse investment and strategic considerations such as:

- the location and size of warehouses;
- which materials to recycle, what fraction of them, and when, given fluctuating market prices;
- how to allocate MSW to the different waste management options within the hierarchy; and
- the effectiveness of various policies to increase the MSW recycling rate, such as landfill bans and subsidies to recycling operations.

This paper does not address the timing of the warehouse investment. We assume that all the inventory warehouses are built at the beginning of the three-year planning horizon. We have formulated an MINLP model to answer the time-to-invest question; however, it is a more difficult problem to solve and is left for future work.

The paper is structured in the following manner. Section II describes the system configuration for model development. Section III discusses our model caveats. Section IV provides the detailed model formulation for the MSW recycling system with inventory warehouses. Section V discusses a case study and the dataset used. Section VI provides analysis results for seven different scenarios; finally, Section VII discusses our conclusions and recommendations for future research.

## 2. System Configuration

Figure 2 shows the diagram of a generic MSW recycling system based on the model of the system in Montgomery County, Maryland. We assume the MSW is collected at curbside. The MSW system includes waste generators, material recycling facilities (MRFs), inventory warehouses, and landfill sites. No transfer station or waste-to-energy facility is considered in the current version of the model. Collected nonrecyclable solid waste is sent to the landfill directly. Recyclable MSW (in this research, we assume that recyclable waste stream is a homogeneous mixture of five different materials: paper, glass, steel, aluminum and plastics) is collected separately and sent to MRFs for sorting and processing. We assume that paper is separated from the rest of the recyclable waste stream immediately upon arrival at the MRF. The recycled paper can then be sent to a warehouse or landfill, or else it can be sold on the recycled paper market. The rest of the recyclable waste stream is then sent to the sorting facility.

Using various physical processes, such as magnetic and gravity separation techniques, glass, steel, aluminum, and plastics are then separated. The separated materials move on to a warehouse for storage or are sold on the secondary material markets. Recyclable material may be sent to a landfill if the quantity of the nonpaper recyclable waste stream is larger than the MRF's processing capacity or the capacity of the warehouse, or if there is no demand for the material on the secondary materials market. In these cases, municipalities should consider paying a contractor to take the recyclable materials, as long as the contractor's charge is less than the cost of tipping fee plus the transportation costs from the MRF to the landfill. In the recycling model presented in this paper, the candidate sites of inventory warehouses are assumed to be collocated with MRFs. This assumption can be easily relaxed if the location information of potential warehouses is available.

## 3. Model Caveat

The goal of this research is to demonstrate the potential of an inventory warehouse to reduce the net present value of a MSW recycling program cost for given assumptions of the planning horizon and discount rate. The full set of assumptions is:

- curbside collection only;
- the composition of MSW is the same for each individual generator, and the total quantity of MSW generation will increase at 1.2% per year but the composition stays the same for the entire planning time periods;
- warehouses are collocated with MRFs (ignore the transportation distance/cost between MRF and warehouse);
- the prices of recycled materials are given exogenously (the amount of recycled materials from each individual MRF is small and they are unable to influence the market prices);

- warehouses are built at the beginning of the planning time period, although some warehouses will not start banking at the beginning of the planning time period; and
- quarterly cash flows.

## 4. Recycling System Model Formulation

In this section, we discuss in great detail the nonlinear dynamic optimization model for the planning of MSW recycling system infrastructure and for the design of recycling strategies. The objective function and constraint sets are described below.

### *Objective Function*

The objective function of this MSW recycling model is to minimize the discounted cash flow of all system costs and revenues over a three-year planning horizon. The costs are:

- MSW transportation cost from generators and MRFs to landfill sites;
- recycled materials transportation cost from MSW generators to MRFs;
- recycled materials sorting and processing cost;
- tipping fee at all landfill sites; and
- capital and O&M costs of the secondary material inventory warehouses.

The first four cost components are expressed in equations (1) to (4), respectively (below). The costs for the warehouse will be discussed separately in a later section. Equation (4) deserves special attention. In this model, we allow different tipping fees for different recyclable and nonrecyclable materials. This gives us more flexibility to charge different tipping fees for different materials at landfill sites. It allows us to investigate the possibility of increasing recycling rate for certain specific materials by charging higher tipping fees. We will discuss this in a later section.

$$TRAN1_t = \left[ \begin{array}{l} \sum_i \sum_l (NR_{ilt} + R1_{ilt}) * D_{il} + \\ \sum_m \sum_j \sum_l LF_{mjlt} * D_{jl} + \sum_j \sum_l UNSORT_{jlt} * D_{jl} \end{array} \right] * TC_1 \qquad \forall t \qquad (1)$$

$$TRAN2_t = \sum_i \sum_j R2_{ijt} * D_{ij} * TC_2 \qquad \forall t \qquad (2)$$

$$MRFC_t = \sum_j SORT_{jt} * SC + \sum_j \sum_m RECYCLE_{mjt} * CC_m \qquad \forall t \qquad (3)$$

$$\begin{aligned} TFEE_t &= \sum_l \sum_i (NR_{ilt} * TFEE) \qquad \forall t \qquad (4) \\ &+ \sum_l \sum_j \sum_m (LF_{mjlt} * TFEE_m) \\ &+ (\sum_l \sum_i R1_{ilt}) * (\sum_m (COMP_m * TFEE_m) + (1 - \sum_m COMP_m) * TFEE) \\ &+ (\sum_j \sum_l UNSORT_{jlt}) * \sum_m \frac{COMP_m * TFEE_m}{\sum\limits_{\substack{m \\ m \neq PAPER}} COMP_m} \end{aligned}$$

### *Capital and O&M Costs at Inventory Warehouse*

The development of a capital cost function for a recycling inventory warehouse is not an easy problem to solve. Examples of factors that need to be considered include the automation level, storage and handling equipment and, perhaps, regional factors such as land acquisition cost. The recycling literature specifically discusses these issues—for example, Bodner et al. (2002).

This paper assumes the inventory warehouse cost model shown in Equation (5). This equation assumes that the capital cost of an inventory warehouse is a simple polynomial function of warehouse volume, where *a* is the cost function parameter and *b* is the scale factor. We assume that *b* has value between 0 and 1, which means the capital cost shows an economy of scale.

$$a_j(CAPV_j)^{b_j} \qquad \forall j \qquad (5)$$

As we mentioned before, the current model does not address the issue of when to invest in a warehouse. We assume that all necessary warehouses are built at the beginning of the planning horizon. We further assume that every warehouse has a 20-year lifetime. However, costs, prices, and revenues for the recycling system will be analyzed on a three-year basis. Using a fixed quarterly interest rate *r*, the amortized quarterly capital cost for each warehouse is expressed by Equation (6), and the amortized quarterly capital cost for all warehouses in the system is given by Equation (7).

$$A_j = a_j(CAPV_j)^{b_j} * (A/P, r, 80) \qquad \forall j \qquad (6)$$

$$WCC_t = \sum_j A_j \qquad \forall t \qquad (7)$$

We assume that O&M cost of inventory warehouse in a specific time period can be expressed similarly using a simple polynomial function of total volume of banked secondary materials during that time period. The total O&M cost for all inventory warehouses in a specific time period is expressed in Equation (8), where $c_j$ and $d_j$ are site-specific parameters in the O&M cost function. For example, a rural area may have lower labor costs.

$$WOM_t = \sum_j c_j(VINV_{jt})^{d_j} \qquad \forall t \qquad (8)$$

Equation (9) is the only revenue component considered in the objective function. It includes the revenue from selling all the secondary materials from all the MRFs in the system, at their market prices.

$$TR_t = \sum_j \sum_m SE_{mjt} * MP_{mt} \qquad \forall t \qquad (9)$$

The objective function is to minimize the discounted cash flow of all systems costs minus revenue, over time. A planning horizon of three years is used to illustrate the model. The complete objective function is expressed in Equation (10), where *r* is the quarterly discount rate.

$$Z = \sum_t \frac{TRAN1_t + TRAN2_t + MRFC_t + TFEE_t + WOM_t + WCC_t - TR_t}{(1+r)^t} \qquad (10)$$

## *Constraint Set*

The constraint sets consist of waste generation, waste allocation, the mass balances at each facility and recycling process within the MSW system, warehouse capacity, recycling program, recycling rate, and landfill ban. We discuss these constraints below.

### Waste Generation

We assume that the generation of MSW increases at a fixed growth rate *g*, given by Equation (11). For simplicity, we further assume that the composition of recyclables in the MSW stream is also fixed over the entire planning horizon. We consider the MSW stream to include nonrecyclable materials along with five types of recyclable materials: paper, glass, steel, aluminum, and plastics. These assumptions can be easily relaxed depending on data availability for specific cases.

$$G_{it} = G_{io} * (1+g)^t \qquad \forall i,t \qquad (11)$$

### Mass Balance at Generator

In our MSW system configuration, all waste generated at sources is shipped to either landfill sites or MRFs. The MSW generated at each municipality *i* includes three different categories: nonrecyclable (*NR*) materials, recyclable materials that are not recycled (*R*1) due to economic or other reasons, and actually recycled materials (*R*2). The first and the second waste categories are sent to landfills. The third waste category is sent to MRFs. The mass balance at generator *i* for specific time *t* is given by Equation (12).

Equations (13) and (14) provide tighter bounds for material flow variables. Equation (13) says that the flow of nonrecyclables sent from municipality *i* to all landfill sites *l* must be equal to all nonrecyclables generated from *i*. Equation (14) says that recyclable but not recycled plus actually recycled materials should be equal to all recyclable materials generated from *i*.

$$G_{it} = \sum_{l} NR_{ilt} + \sum_{l} R1_{ilt} + \sum_{j} R2_{ijt} \qquad \forall i,t \qquad (12)$$

$$\sum_{l} NR_{ilt} = G_{it} * (1 - \sum_{m} COMP_{m}) \qquad \forall i,t \qquad (13)$$

$$\sum_{l} R1_{ilt} + \sum_{j} R2_{ijt} = G_{it} * \sum_{m} COMP_{m} \qquad \forall i,t \qquad (14)$$

### Recycling Program

Constraint (15) is a recycling program constraint for the entire system. *PROG* is a 0–1 parameter. If *PROG* is set to 0, it means there is no recycling program for the entire system. If *PROG* is equal to 1, it means that recycling is allowed. In Constraint (15), *BIGM* is a parameter with a very large value. If *PROG* is equal to 0, then the right–hand side (RHS) of the constraint will be equal to 0. Since all variables are non-negative, the constraint will force all variables *R*2 to be zero. This means there will be no recyclable material flows from generator *i* to any MRFs, *j*. It is a way to say there is no recycling program for the entire system. On the other hand, if 1 is assigned to *PROG*, then RHS of the inequality is a very large number. In that case *R*2 does not have any upper bound and the constraint becomes redundant.

$$\sum_i \sum_j R2_{ijt} \leq BIGM * PROG \qquad \forall t \qquad (15)$$

## Paper Received

Based on our experience with a recycling center in Montgomery County, Maryland, paper is separated from the waste stream immediately upon arrival at the MRF. Since it does not go through the sorting facility with the other recyclable materials, we track the paper flow separately. The paper for recycling is either stored, sold, or sent to a landfill.[1] Since we assume the composition of recyclable materials from all generators is the same, the total amount of paper received at a specific MRF *j* and time period *t* can be expressed using Equation (16).

$$PAPER_{jt} = \sum_i R2_{ijt} * COMP_{PAPER} / \sum_m COMP_m \qquad \forall j,t \qquad (16)$$

Equation (17) says that the inventory of paper at a specific MRF *j,* at time period *t,* is equal to the previous inventory plus the paper received for the current time period minus the paper sold and sent to the landfill.

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[1] Sending recycled material to a landfill is a last resort. This is because one has to pay the transportation cost and tipping fee at the landfill. It is probably more economic to either store the material, sell it at the going market price or even pay someone to take it, as long as the cost is cheaper than the cost of disposal via landfilling.

$$INV_{PAPERjt} = INV_{PAPERjt-1} + PAPER_{jt} - \sum_{l} LF_{PAPERjlt} - SE_{PAPERjt} \qquad \forall j,t \qquad (17)$$

Equation (18) defines the amount of paper recycled at a MRF *j,* during time period *t*. Paper recycled at MRF *j* during time period *t* is defined as paper received at *j* minus paper sent to landfill sites during this time period *t*. This recycled paper can be either stored, thereby increasing the inventory in the warehouse, or it can be sold on the secondary material market.

$$\begin{aligned} RECYCLE_{PAPERjt} &= INV_{PAPERjt} - INV_{PAPERjt-1} + SE_{PAPERjt} \qquad \forall j,t \qquad (18) \\ &= PAPER_{jt} - \sum_{l} LF_{PAPERjlt} \end{aligned}$$

### Nonpaper Recyclable Material Received

Equation (19) is the quantity of the nonpaper recyclable waste stream, which includes glass, steel, aluminum, and plastics received at MRF *j*.

$$NONPAPER_{jt} = \sum_{i} R2_{ijt} - PAPER_{jt} \qquad \forall j,t \qquad (19)$$

### Mass Balance at Sorting Facility

If the nonpaper recyclable material received is greater than the capacity of the sorting facility, then only part of the waste stream will be sorted. Unsorted waste is sent to a landfill. Equation (20) says the nonpaper recyclable material flow is the sum of the sorted and unsorted flows, which are sent to sorting facilities and landfill sites, respectively. Constraint (21) says the amount of waste that gets sorted is bounded above by the sorting capacity at each MRF *j*.

$$NONPAPER_{jt} = \sum_{l} UNSORT_{jlt} + SORT_{jt} \qquad \forall j,t \qquad (20)$$

$$SORT_{jt} \leq SORTCAP_{j} \qquad \forall j,t \qquad (21)$$

## Recycling Constraint

Equation (22) is similar to Equation (18). It is the MRF mass balance equation for recyclable materials other than paper.

$$\begin{aligned} RECYCLE_{mjt} &= (SORT_{jt} * COMP_{m}) / \sum_{\substack{m \\ m \neq PAPER}} COMP_{m} - \sum_{l} LF_{mjlt} \qquad \forall m \setminus \{PAPER\}, j,t \qquad (22) \\ &= INV_{mjt} - INV_{mjt-1} + SE_{mjt} \end{aligned}$$

## Capacity Constraint

The volume of all secondary inventory materials at any MRFs during any time period should be bounded by the capacity of the inventory warehouse at that MRF. Using compressed secondary material weight-to-volume conversion factors from the United States Environmental Protection Agency (USEPA 1997), we derive the volume of recycled material in the warehouse. We consider a 100% safety factor for the working space. Equation (23) is the total space required at warehouse *j*, during time period *t*. Constraint (24) says the total space at warehouse *j* during any time period (taken to be one quarter) is bounded above by its capacity. Thus, the total space requirement is the volume of inventory multiplied by 2.0.

$$VINV_{jt} = \sum_{m} (INV_{mjt} * WT2VOL_{m}) * 2.0 \qquad \forall j,t \qquad (23)$$

$$VINV_{jt} \leq CAPV_j \qquad \forall j,t \qquad (24)$$

Constraint (25) means for each landfill site *l*, the waste received from all waste generators *i* and MRFs *j* during any time period *t* should not exceed its capacity.

$$\sum_j \left(\sum_m LF_{mjlt} + UNSORT_{jlt}\right) + \sum_i NR_{ilt} + \sum_i R1_{ilt} \leq CAPW_l \qquad \forall l,t \qquad (25)$$

## Recycling Rate

The recycling rate for a specific time period is defined as material(s) recycled at all MRFs divided by total MSW generated during that time period. Equation (26) defines the entire system's recycling rate for the quarterly time period *t* for all materials. Equation (27) does the same for a single material *m*. Constraints (28) and (29) are the minimum recycling rate of the entire systems for all materials and for individual materials, respectively.

$$TRR_t = \sum_j \sum_m RECYCLE_{mjt} / \sum_i G_{it} \qquad \forall t \qquad (26)$$

$$MRR_{mt} = \sum_j RECYCLE_{mjt} / \sum_i G_{it} \qquad \forall m,t \qquad (27)$$

$$TRR_t \geq MINTRR \qquad \forall t \qquad (28)$$

$$MRR_{mt} \geq MINMRR_m \qquad \forall m,t \qquad (29)$$

## Landfill Ban

Some states have banned recyclables from landfill sites. For example, in 1989, Rhode Island prohibited landfills from accepting commercial solid waste with more than 20% designated recyclables in them (Porter 2002). To account for landfill bans, this model can simulate the effect of restricting specific recyclable materials from all landfills within the MSW system. This is done by adding the constraint in Equation (30) for each individual recyclable.

$$\sum_i \sum_l R1_{ilt} * COMP_m + \sum_j \sum_l UNSORT_{jlt} * (COMP_m / \sum_{\substack{m \\ m \neq PAPER}} COMP_m) \quad \forall m, t \qquad (30)$$

$$+ \sum_j \sum_l LF_{jmlt} \leq BIGM * (1 - BAN_m)$$

The left–hand side of this constraint accounts for the total material flow of material *m* from all sources that is received at all landfills in the MSW system. $BAN_m$ on the right–hand side (RHS) of the constraint is a 0 or 1 parameter. When $BAN_m$ is equal to 1, it means that material *m* is banned from all landfills in the system; when $BAN_m$ equal to 0, it means otherwise. $BAN_m$ equal to 1 makes the RHS of the constraint equal to 0 and forces the material flow to be zero at all landfills. This simulates a total ban on the material *m* at all landfills in the system. When $BAN_m$ is equal to 0, the constraint is redundant and there is no ban on material *m* at landfills.

One alternative to a landfill ban is to set $MINMRR_m$ equal to the composition of material *m*, in the waste stream. This means recycling all of material *m* is equivalent to a landfill ban on material *m*. One can also increase the landfill tipping fee for any specific material *m*, in order to reduce the amount of material *m* sent to the landfills. The policy is only feasible in the unlikely cases where the materials are sent to the landfill after sorting, since it would be difficult to assess the composition of the unsorted waste stream when it is tipped for disposal at the landfill. Some enforcement effort is required to make a landfill ban effective. However, the policies for such enforcement are beyond the scope of this paper.

So far, we have completed the model development for this research. It is a nonlinear dynamic optimization model. A nonlinear programming solver, CONOPT, in GAMS, is used to solve this model.

## 5. Case Study

In order to test the assumption that an inventory warehouse could result in lower net cost for recycling MSW, and to examine other questions about MSW recycling policy, we simulated an MSW management system based on the model of Allegheny County, Pennsylvania. This system consists of 133 municipalities, 13 landfill sites, and 9 MRFs. Data on the location, capacity, transportation costs for MSW and recycled materials, and estimated MRF processing costs and tipping fees at landfill sites are derived from the 1993, 1994, and 1995 annual reports on MSW management from the Allegheny County Sanitary Authority (Louis 1996). In order to simplify the mass balances and materials flows for the model, we aggregated the 133 municipalities in the Allegheny County system into 26 pseudo–municipal districts. The MSW generation and growth rates, and the composition of MSW are from Franklin Associates (1997). Compressed secondary material weight to volume conversion factors are from EPA (USEPA 1989; USEPA 1997). The market prices of secondary materials are from California integrated waste management study (California Integrated Waste Management Board 1996).

The total population of the municipalities selected was 1,333,000 in 1996. At the starting rate of 4.2 pounds of MSW per person per day, the total generation of MSW in the first quarter was 255,422 tons. Using the MSW composition data presented in Table 3 resulted in a value of 57,000 tons per quarter of MSW for sorting, excluding paper, which we assume is not mixed with the other components of the recyclable waste stream.

### *Basic Data*

Table 1 provides the capacity information for the 13 landfills in Allegheny County.

### *MSW Recycling System Layout*

The MSW system includes 26 municipality centers, 9 MRFs, and 13 landfills. The system layout for the case study is shown in Figure 3. The distance matrices among these facilities are calculated using straight-line distance measurements multiplied by a factor of 2.5.

### *Secondary Material Market Prices*

The market prices of secondary materials are obtained from California Integrated Waste Management Study (1996). Figure 4 shows the time series of quarterly market prices for five different secondary materials.

### *Cost Function Parameters*

Table 2 contains various cost function parameters used in this paper. The value of $a$ is calculated using warehouse quick cost calculator at http://www.rsmeans.com/ (R.S. Means Company, Inc. 2002). The calculator gives cost per square feet. We converted it to square yards and assume each warehouse is six yards tall. Using the cost and warehouse volume, we estimate the capital cost is about $65.6 per cubic yard. The cost figure includes the contractor's overhead and profit and architectural fees, but it does not include land cost.

### Other Basic Data

Table 3 contains the MSW composition by weight percentage. Table 4 provides the weight-to-volume conversion factor used in the case study.

## 6. Analysis Results

This study attempts to answer seven questions about recycling with an inventory warehouse system:

> *Question 1: Is an inventory warehouse justified in the case of a regime of uniform prices for secondary materials, or only in the case of fluctuating prices?*
>
> *Question 2: What savings does an inventory warehouse contribute to the cost of a MSW recycling system?*
>
> *Question 3: What effects do the recycling rate and total warehouse capacity have on recycling system cost?*
>
> *Question 4: How sensitive is the total recycling system cost to the materials transportation cost?*

*Question 5: What is the relative effectiveness of policies to stabilize secondary materials prices and to reduce materials transportation cost, respectively?*

*Question 6: How does the price history of a given recyclable material affect the portfolio of recyclables stored in the inventory over multiple operating periods?*

*Question 7: What is the effect of recycling bans on the quantity of material recycled?*

For each question there is a corresponding analysis. Costs in each analysis are calculated for a short-term planning horizon of three years, broken into quarterly operating periods of three months each. Thus, each analysis examines historical materials prices for 12 consecutive quarters and computes the discounted net present value of the MSW recycling system cost, assuming quarterly compounding over this period. A total of 35 runs of the optimization model were made to answer the seven questions posed for analysis. Table 5 summarizes the values of the system variables used in each run of the model, as well as the corresponding value of the objective function for each run.

### *Analysis 1: The Necessity of Inventory Warehouse*

Analysis 1 compares the system revenue for uniform average prices for each material over the 12 planning periods against the revenue for actual historical prices for the materials during the same period. In Figure 1 we used a simple case to show that the revenue from recycling could be maximized if all the material of a given type that was collected in a given time period could be sold at the maximum price that occurred during that period. Analysis 1 seeks to demonstrate that an inventory warehouse is needed only when the market prices of the secondary materials fluctuate.

We examine the results of two runs. In R31, each material is assigned a uniform price based on the average of its actual prices during the 12 quarters used for the analysis. In R4, which is used for comparison, the actual quarterly prices of each material are used. Table 6 summarizes the results. The results in Table 6 show that when market prices are uniform (R31), no warehouse is necessary and the inventory of each material is zero. The recyclable materials are collected, sorted, and sold on the market immediately. Furthermore, the recycling rates are constant for all quarters during the three year period. On the contrary, when material prices fluctuate (R1), as they do in the real world, inventory warehouses permit the MSW recycling systems to exploit the price variation by banking materials for sale at the highest expected market prices. This assumes a perfect predictor of future market prices and is subject to the capacity of the warehouse. Since the municipality can maximize its revenue from the sale of recyclables under this scenario, the net cost of the recycling program will be reduced if the cost of constructing and operating the warehouses is less than the increased revenue from the inventory-based recycling scheme. For the case of uniform materials prices, the objective function has a value of $57 million. However, when prices fluctuate and a warehouse of 15,000 cubic yards is added, the system cost drops to $47 million—a savings of 21%.

Note that if market prices of recyclables are decreasing, there will be no reason to bank these materials. They will be collected, sorted, and sold at current market prices in order to maximize revenue. Conversely, if market prices of materials are expected to increase steadily during a given period, then the inventory should be kept at maximum capacity during this period, with daily sales only when warehouse capacity is exhausted. This assumes perfect knowledge of future prices and that the market can absorb all of the municipality’s inventory at the point of sale.

### *Analysis 2: Cost Saving Potential of Recycling and Inventory Warehouse*

We have demonstrated that it is only feasible from a cost perspective to build an inventory warehouse when the price of secondary materials is fluctuating or steadily increasing. In the second analysis, we compare the costs of three different MSW management systems: no recycling, unlimited recycling capacity with no inventory warehouse, and unlimited recycling with unlimited inventory warehouse capacity. Keeping all other assumptions constant, this comparison will permit us to assess which of these alternatives has the lowest net systems cost during a three-year cycle of secondary materials prices. The results of this study are summarized in Tables 7a and 7b. Table 7a shows the inventory of materials for the entire 12-quarter period.

Table 7b shows total materials recycled, including inventory and sales for the entire period. R1 represents the system with no recycling and no inventory. R2 represents the system with recycling without an inventory warehouse. R3 represents the system with both recycling and inventory warehousing. The system with no recycling or inventory has a net cost of $81 million over three years. When recycling is added but no inventory warehousing is available to exploit the fluctuation in materials prices, the net systems cost drops to $42 million over three years. This represents a savings of $39 million or 48% over three years. When warehousing capacity is added, the three-year net system cost drops to $38 million. This represents a three-year savings of $43 million or 53% over the system with no recycling. It represents a three-year savings of $4 million or 10% over the recycling system with no warehousing.

The cost of building the warehouses is included in the calculation of these savings. Thus, in this simulation with perfect knowledge of the secondary materials market prices over a three–year period, the addition of an inventory warehouse for recyclables is the least-cost alternative for managing MSW.

### *Analysis 3: MRFs Sorting Capacity and Warehouse Capacity*

The previous analysis showed that recycling with warehouse capacity can be the least cost alternative for operating a MSW recycling system in the face of fluctuating market prices. This analysis assesses the impact of sorting capacity and warehouse capacity on the net system cost as a function of the recycling rate. The results are summarized in Figure 5.

In R4 to R9, the sorting capacity is set at 15,000 tons per quarter and the storage capacity at 15,000 $yd^3$. This explains the legend “15k, 15k” in Figure 5. The minimum recycling rate is increased by 10% in each run from 0% in R4 to 50% in R9. As expected, there is a steady increase in net system cost as the recycling rate is increased with all other variables held constant.

In R10 to R15, the effect of storage capacity is examined by reducing the storage capacity to 5,000 $yd^3$ at each MRF while keeping the sorting capacity fixed at 15,000 tons per quarter. Once again, the recycling rate is increased by 10% for each run, starting at 0% for R10 and ending at 50% for R15. These results show that the cost for each recycling rate is higher than for the case where storage capacity was 15,000 $yd^3$. This is to be expected, as there is insufficient inventory capacity to store all the material that is sorted and the surplus from sorting has to be sold at the going market price. This results in less than maximum revenue realized from the sale of materials.

In R16 to R21, sorting capacity is reduced to 5,000 tons per quarter at each MRF and storage capacity is held at 5,000 $yd^3$. Again, the recycling rates are varied from 0% to 50% in increments of 10%. When these results are compared by recycling rate to the previous case, it is apparent that reducing the sorting capacity results in an increase in net system cost at all recycling rates. Again, this increase may be explained by the fact that reducing the amount of recyclables sorted effectively reduces the amount of material that can be recycled. The unsorted recyclables bypass the MRFs and go to the landfill, where they do not earn revenue for the system.

In R22 to R27, sorting capacity is held at 5,000 tons per quarter at each MRF, and storage capacity is increased to 15,000 $yd^3$. Recycling rates are varied from 0% to 50% in increments of 10%. This combination of sorting and storage capacity results in the highest net system cost considered. This occurs because the municipality has undertaken the expense of building the inventory capacity but does not have the sorting capacity to utilize the space with recyclable materials. In fact, due to the limited sorting capacity, the municipality is paying the annual capital cost for the warehouses and also paying for the landfill disposal of the recyclables it is not able to sort. Thus, this is the least efficient option from a cost perspective with the associated highest net system cost.

These results support the heuristic expectation that sorting capacity is a greater determinant of system cost than warehouse capacity, when either sorting or storage capacity is less than the total amount of recyclables received at an MRF. This analysis assumes uniform sorting and storage capacities at all MRFs in the system. However, in reality, each MRF is likely to have a different sorting and storage capacity. In this case, transportation distance and per unit transportation cost become determinants in the net system cost, as recyclables that exceed the sorting capacity of their closest MRF must be transported to more distant MRFs for sorting.

### *Analysis 4: Sensitivity of TC2*

Based on the results of Analysis 3, it is natural to examine the sensitivity of total system cost to transportation cost (*TC*2). This comparison in made between R4 and R28. In R4, the materials transportation cost is \$15 per ton mile. In R28, the unit transportation cost is reduced 10% to \$13.5 per ton mile. This 10% reduction in per unit transportation cost results in a 12.8% reduction in net system cost. Table 8 shows the recycling rate per period for each scenario. By reducing the transportation cost, the recycling rates in R28 are consistently equal to or greater than the rates in R4. This observation implies that municipalities could reduce their recycling program costs by searching for alternatives to reduce their transportation costs of recyclables. Essentially, this means seeking ways to reduce the collection cost of recyclables. This simple sensitivity test in not sufficient to fully justify such a policy recommendation. However, it is sufficient basis for evaluation as future work.

### *Analysis 5: Increasing the Recycling Rate by Subsidizing the Recyclable Material Market Price*

The analyses conducted in this study are based on perfect knowledge of the quarterly market price for recycled materials over a three-year period. In reality, there will be considerable uncertainty over future market prices. Municipalities are not likely to maximize their revenue from recyclables, even with the use of an inventory system, because their knowledge of the maximum price of each class of recyclable will be imperfect at the point of sale. In Analysis 1, it was demonstrated that there is no inventory in the event of constant quarterly secondary materials prices. Furthermore, it also was argued that, in the case of steadily increasing prices for recyclables, the optimal strategy would be to hold the maximum amount of recyclables in inventory (reserving space for each material type in order of its respective market price) and sell only the amount that exceeded storage capacity in each quarter.

Analysis 5 compares the sensitivity of net system cost and recycling rate of constantly escalating market prices against the sensitivity of net system cost and recycling rate of reductions in the materials transportation cost *TC*2. The comparison is based on an assumed 10% per quarter increase in the market price of recycled paper. The historical quarterly prices of the other recyclables are not affected. Paper is selected because it is the predominant constituent of the recycled materials stream. At 64% of all recyclable material, it is four times more abundant than the next most prevalent material.

R4 represents the case of historical prices for all types of recyclables. R29 represents the case of the 10% per quarter increase in the price of paper and historical prices for all other materials. The results shows that the net cost of the recycling system is reduced by about 10%. Table 9 compares the quarterly recycling rates for R4, R28, and R29.

R28 was discussed in Analysis 4. It examined the effect of reducing the materials unit transportation cost by 10% while holding all other variables constant. The results for R28 show that a reduction in unit transportation cost more effectively increases the recycling rate than does a steady increase in the price of paper and lowers the net system cost by 14%, compared to 10% for the increase in the price of paper. Though the full effect of price supports for recyclables cannot be fully explored by the simple assumption of an increase for paper alone, this illustration shows that reducing the unit transportation cost of recyclables could be a more effective way to boost the recycling rate and reduce the net cost of MSW recycling than price supports for recycled materials.

### *Analysis 6: Price Effects on the Portfolio of Recyclables*

When warehousing capacity is limited, increases in the market price of one specific material will result in changes in the portfolio of recycled materials held in storage. In order to store greater amounts of the more lucrative material, the less lucrative recyclables will be sold from the warehouse. In Analysis 6, a warehouse capacity of 5,000 yd$^3$ is assumed for reach MRF. The steel price is increased by $100 per ton for periods 7, 8, and 9. In Tables 10a and 10b, respectively, the quantity of materials banked in the inventory warehouse before (R32) and after (R33) the price change is compared. As the base case results in Table 10a show, no steel is banked in the warehouse. The market price for steel in the base case is flat and stable. Thus, recycled steel is sold in the market immediately and no banking is necessary. However, when the steel market price is increased for periods 7, 8, and 9, steel is banked at period 4. Furthermore, the banking of paper and aluminum are reduced in periods 4, 5, and 6 as the space is reserved for and substituted by more valuable steel.

### *Analysis 7: Recycling through Cost Incentive: Landfill Ban and/or Graduated Tipping Fees*

Analysis 7 explores the effect of a landfill ban on the recycling portfolio and the net cost of the recycling system. R34 examines the effect of a landfill ban on paper. R30 examines the effect of a landfill ban on aluminum. Tables 11a and 11b summarize the results for the paper (R34) and aluminum (R30) bans respectively.

Since paper is segregated from the other components of the recycled waste stream prior to sorting at the MRF, a landfill ban on paper will simply increase the amount of paper that must be warehoused. Operationally, this ban means that the diverted paper must be transported to MRFs rather than landfills. Thus, the higher materials transportation cost and the lost revenue from selling this low-priced recyclable at less than optimal prices result in a sizeable increase in the net recycling system cost.

In the case of any recyclable material other than paper, as illustrated by the example of aluminum, a landfill ban implies that the entire nonpaper recyclable stream must go through sorting at the MRF. No recyclables are allowed to bypass the MRF and go directly to the landfill because this stream may contain the component that is banned from landfilling. Once sorted, all recyclable materials are available for either sale or warehousing depending on the market price for recyclables and the storage capacity of the warehouse. The ban on nonpaper recyclables exerts cost pressure on the system in two ways. Firstly, it increases the total materials transportation cost to MRFs. Since the net systems cost is relatively sensitive to the recyclable materials transportation cost, the result is a significant increase in net cost due to the landfill ban. Secondly, when the total amount of material available for storage exceeds the storage capacity of the MRFs, the excess material must be sold at the going market price. This portion of the recyclable stream does not benefit from the price advantage gained by warehousing. As a result, the revenues from sale of recyclables are not maximized and net systems cost are not minimized.

One way to discourage landfilling of a given material without an outright landfill ban is to set a discriminatory or graduated tipping fee for that material. Table 12 shows the newspaper recycling rates under three different policies. R4 uses the standard tipping fee of $15 per ton for all materials including newspaper. R34 represents a landfill ban on newspaper. R35 represents a tenfold increase in the tipping fee for newspaper of $150 per ton.

The landfill ban on newspaper may increase the newspaper recycling rate, but it also increases the net systems cost from $47 million to $172 million over the three–year period. This is a 266% increase in net system cost. Thus, from a cost perspective, the landfill ban would not be an attractive policy.

A discriminatory, tenfold increase in the tipping fee for newspaper would certainly discourage users from sending this material to the landfill. This increases the newspaper recycling rate, as Table 12 shows. However, the result is an increase in net system cost from $47 million to $98 million over three years. This is a 109% increase. Though significantly less than the increase from a landfill ban, this is still a large percentage increase, and the municipality may want to weight the benefit of a higher recycling rate against the higher cost associated with that policy.

## 7. Conclusions and Recommendations

### *Conclusions*

The goal of this paper was to determine whether the use of an inventory warehouse could reduce the net cost of recycling municipal solid waste. Using three years of quarterly prices for a portfolio of recyclable materials (paper, plastic, steel, aluminum, and glass), a nonlinear dynamic programming model was developed to determine the market price regime under which recycling with an inventory system would reduce net system cost. In addition, the model was used to answer several policy questions related to the optimal strategy for managing the recycling system. These questions were:

1. *What are the savings from recycling with inventory?*
2. *How do the recycling rate and warehouse capacity affect system cost?*
3. *How sensitive is the net system cost to materials transportation cost?*
4. *How does a policy to reduce materials transportation cost compare to a policy of price supports for recycled materials in reducing net system cost?*
5. *How does the market price of one recyclable material affect the portfolio of materials held in inventory?*

6. *What is the effect of landfill bans on selected recyclable materials on the portfolio of recyclables and the net system cost?*

The first result suggested that, when minimizing net recycling system cost is the primary objective, recycling with inventory was effective only when prices were fluctuating or steadily increasing. It was not cost effective to use an inventory for recycling when prices were constant or steadily decreasing over time.

In the case study it was found that, of the three options (no recycling, recycling without inventory, and recycling with inventory), recycling with inventory had the lowest net system cost because it permitted the municipality to take advantage of the best market prices for individual recyclable materials.

Material transportation costs were shown to exert a significant effect on recycling system cost. Indeed, net system cost was more sensitive to a reduction in materials transportation cost than to price supports for paper, the most abundant component in the recyclable waste stream. Furthermore, a reduction in materials transportation cost did more to increase the overall recycling rate than did price supports for paper. This result suggests that municipalities interested in reducing recycling program costs and increasing recycling rates should consider policies to reduce materials transportation cost before considering price supports for recyclables.

The effect of expected increases in the price of one recyclable component on the portfolio of recyclables was as predicted. Managers would reduce their inventory of less lucrative materials in early cycles, in order to clear storage space for materials expected to increase in price and to contribute significantly to increasing revenue in the future.

Finally, it was found that banning paper from landfills would increase the recycling rate for paper but would increase net system cost by 266%. If discriminatory tipping fees were used instead to discourage landfilling of paper, the recycling rate would increase to about half that achieved by an outright ban, but the net system cost would increase by 109%. In a similar vein, banning other nonpaper recyclables, such as aluminum, from landfills would increase the recycling rate but would greatly increase net system cost. In the case of a landfill ban on aluminum, the net system cost increased from a base value of $47 million to $237 million, or 404%. Thus, if, as we assume, all nonpaper recyclable materials have to be sorted at MRFs in order to comply with a landfill ban on a single nonpaper recyclable component, then the increase to net system cost can be prohibitive, even for a lucrative component as aluminum. This result reflects the fact that there is already a high recycling rate for aluminum without a landfill ban on that material, and imposing the ban only drives up sorting cost without recovering significant increments of aluminum to be sold for revenue.

The model developed for this research also can be used to investigate infrastructure needs and conduct investment planning and analysis. For example, the optimal location and size of inventory warehouses within a municipality's solid waste management program can be determined in order to minimize the recycling system cost. If the cost function for each sort facility is known, an optimal strategic plan for investing in future MRFs can be investigated.

### ***Recommendations***

The current model assumes all warehouses are built and available at the beginning of the entire planning period. However, this investment strategy may not minimize net system cost over the long term. If the market price is flat or decreasing, there is no need to build a warehouse to bank these materials. This research has formulated a mixed integer nonlinear programming (MINLP) model which can answer the question of when to add warehouse capacity. However, the MINLP model is very difficult to solve and can itself be a separate topic. As a result, it is left and recommended for future work.

This research included telephone interviews with MSW recycling program managers. From these conversations, it is clear that their major concern about the investment in inventory warehouses is the uncertainty of future market prices of recyclables. In this regard, the next step is to adopt a stochastic optimization approach based on the current deterministic model. The research is now investigating how to obtain a robust warehouse design given uncertain future market prices.

Finally, this research may consider adding transfer stations and waste-to-energy facilities to the model, in order to assess the effect of these facilities on multi-media risk assessment and on the management of greenhouse gas emissions.

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## Appendix: Notations

### *Definition of sets*

$i$ = waste generator

$j$ = material recycling facility (MRF)

$l$ = landfill site

$m$ = type of secondary material (paper, glass, steel, aluminum, plastics)

$t$ = time period, quarter

### *Definition of variables*

$A_j$ = annualized warehouse capital cost

$BAN_m$ = 0 or 1 parameter for banning material $m$

$BIGM$ = a very large number

$COMP_m$ = waste stream composition for material $m$

$CAPV$ = warehouse capacity in cubic yards (volume)

$CAPW$ = landfill capacity in tons per quarter

$D$ = distance

$g$ = solid waste generation growth rate per quarter

$G_{i0}$ = solid waste generation per quarter at generator $i$ at quarter 0

$G_{it}$ = solid waste generation at site $i$ and time $t$

$IC$ = recycled material inventory cost in dollars per ton

$INV_{mjt}$ = inventory of material m at $j$ and time $t$

$LF_{mjlt}$ = material $m$ recycled at $j$ then sent to $l$ at time $t$

$MINTRR$ = minimum total recycling rate required

$MINMRR_m$ = minimum recycling rate for material $m$

$MP_{mt}$ = market price for secondary material $m$ in time $t$

$MRR_{mt}$ = material $m$ recycling rate at time $t$

$NONPAPER_{jt}$ = recyclable exclude paper received at $j$ at time $t$

$NR_{it}$ = not-recycled material generated at $i$

$NR_{ilt}$ = nonrecyclable waste flow between $i$ and $l$ at time $t$

$PAPER_{jt}$ = recyclable paper received at $j$ at time $t$

$PROG$ = recycling program

r = discount rate

$R_{it}$ = recycled material generated at $i$ at time $t$

$R1_{ilt}$ = recyclable but not recycled flow between $i$ and $l$ at time $t$

$R2_{ijt}$ = recyclable flow between $i$ and $j$ at time $t$

$RECYCLE_{mjt}$ = material $m$ recycled at $j$ stored at warehouse at time $t$

$SC$ = MRF sorting cost in dollars per ton

$SE_{mjt}$ = material $m$ sold at time $t$

$SORT_{jt}$ = recyclable material sorted at $j$ at time $t$

$SORTC_{t}$ = total MRF sorting cost at time $t$

$SORTCAP$ = processing capacity in tons per quarter at MRF $j$

$TC1$ = MSW transportation cost in dollars per ton per mile

$TC2$ = recyclable transportation cost in dollars per ton per mile

$TFEE$ = tipping fee in dollars per ton

$TFEE_{m}$ = tipping fee for specific recyclable $m$

$TR_{t}$ = total revenue from selling secondary material at time $t$

$TRAN1_{t}$ = total MSW transportation cost at time $t$

$TRAN2_{t}$ = total recyclable transportation cost at time $t$

$TRR_{t}$ = total recycling rate for time $t$

$UNSORT_{jlt}$ = recycled material, before sorting, sent to LF from $j$ to $l$ at time $t$

$VINV_{jt}$ = volume of inventory at $j$ at time $t$

$WCC_t$ = warehouse capital cost at time $t$

$WOM_t$ = warehouse O&M cost at time $t$

$WT2VOL$ = weight to volume conversion factor for material $m$ in cubic yards per ton

$a_j$ = parameter in warehouse $j$ capital cost function

$b_j$ = parameter in warehouse $j$ capital cost function

$c_j$ = parameter in warehouse $j$ O&M cost function

$d_j$ = parameter in warehouse $j$ O&M cost function

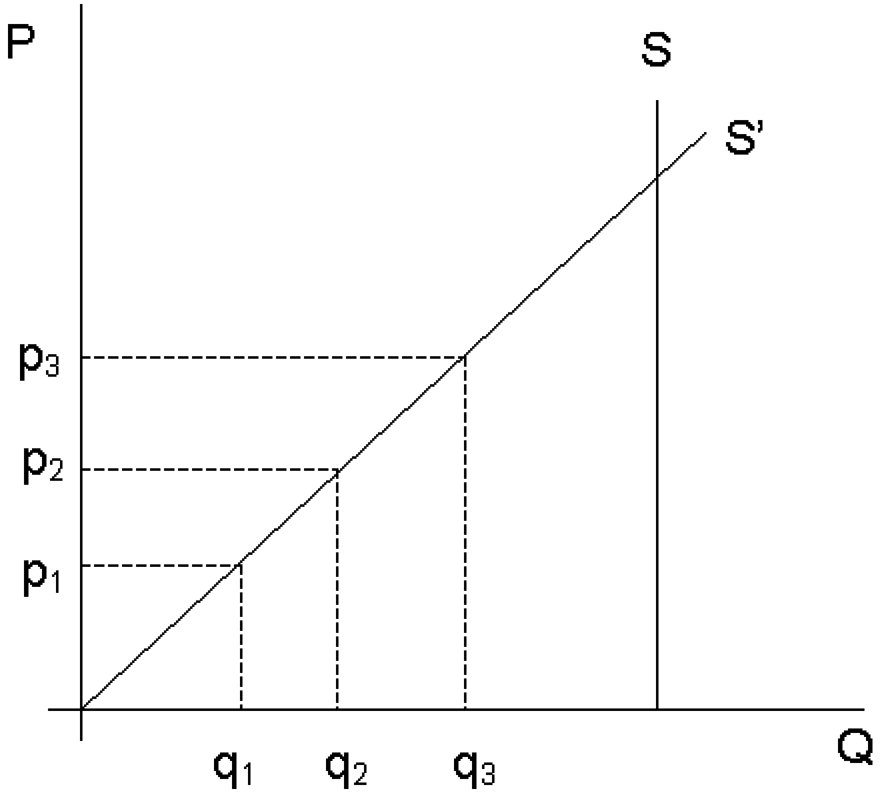

Figure 1. Maximizing the Revenue from Recycling

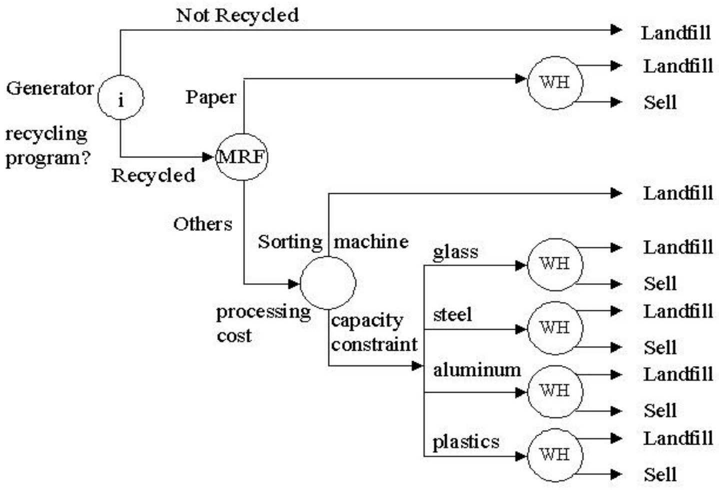

Figure 2. The Configuration of MSW Recycling Systems

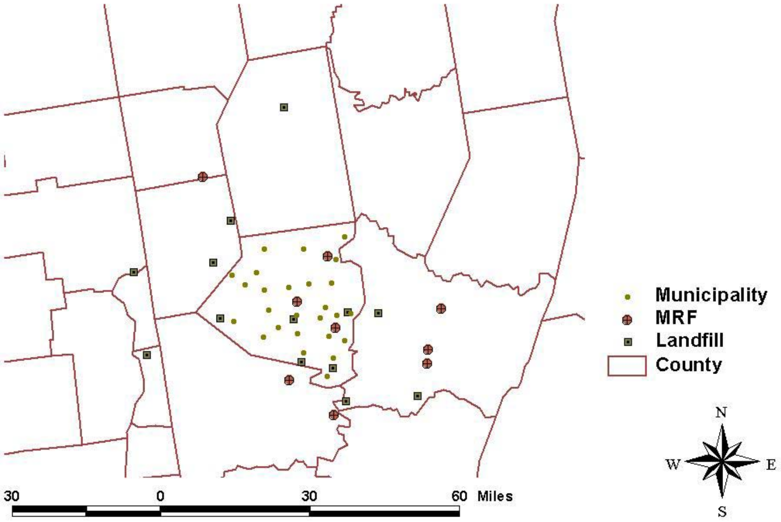

**Figure 3. MSW Recycling System Layout**

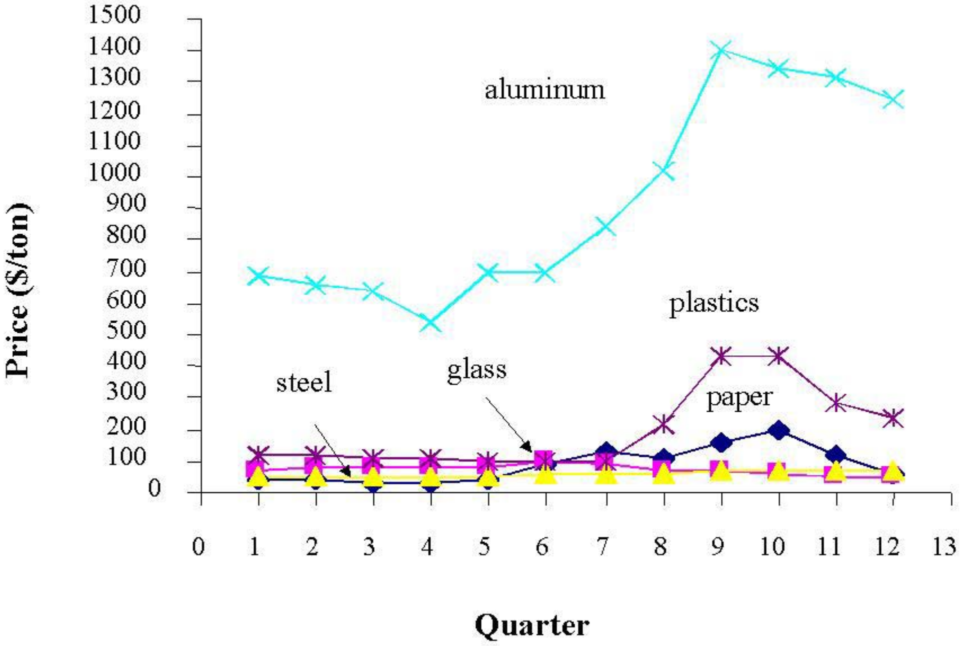

Figure 4. Quarterly Time Series of the Secondary Material Market Prices

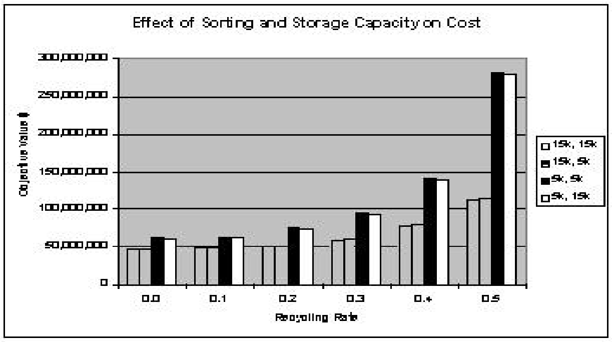

Figure 5. MSW Recycling Cost Curves

## Table 1. Landfill Capacity

| Landfill site no. | Capacity (tons per quarter) |
|---|---|
| 1 | 78,306 |
| 2 | 74,718 |
| 3 | 110,804 |
| 4 | 66,000 |
| 5 | 18,072 |
| 6 | 86,079 |
| 7 | 58,056 |
| 8 | 67,627 |
| 9 | 18,432 |
| 10 | 52,424 |
| 11 | 93,645 |
| 12 | 30,950 |
| 13 | 57,668 |
| **Total** | 812,780 |

## Table 2. Cost Function Parameters

| Parameters | Unit | Value |
|---|---|---|
| $a$ | \$/(cu. yd.) | 65.60 |
| $b$ | | 0.98 |
| $c$ | \$/(cu. yd.-qtr.) | 5.00 |
| $d$ | | 0.98 |
| $g$ | %/qtr | 0.003 |
| $TC1$ | \$/ton/mile | 0.85 |
| $TC2$ | \$/ton/mile | 15.00 |
| $TFEE$ | \$/ton | 15.00 |
| $SC$ | \$/ton | 36.35 |
| $r$ | %/qtr | 0.015 |

## Table 3. MSW Composition

| Item | Composition (wt%) |
|---|---|
| **Nonrecyclable** | 38.5 |
| **Paper** | 39.2 |
| **Glass** | 6.2 |
| **Steel** | 5.6 |
| **Aluminum** | 1.4 |
| **Plastics** | 9.1 |

Source: Franklin Associates 1997

## Table 4. Weight to Volume Conversion Factor

| Item | Factor (cubic yds per ton) | Note |
|---|---|---|
| **Paper** | 2.78 | compacted newsprint |
| **Glass** | 0.89 | mechanically crushed |
| **Steel** | 2.35 | flattened ferrous cans |
| **Aluminum** | 5.88 | flattened |
| **Plastics** | 7.41 | whole compacted HDPE(dairy) |

Source: USEPA 1989; USEPA 1997

## Table 5. Summary of Analysis Runs

| Run no. | Sorting capacity (tons/qtr) | Storage ($yd^3$) | Minimum recycling rate req'd | TC2 ($/ton mile) | Obj. value ($) |
|---|---|---|---|---|---|
| R1 | 0 | 0 | 0.0 | 15.0 | 81,154,778 |
| R2 | 1.50E+08 | 0 | 0.0 | 15.0 | 42,106,520 |
| R3 | 1.50E+08 | 1.00E+06 | 0.0 | 15.0 | 37,623,892 |
| R4 | 15,000 | 15,000 | 0.0 | 15.0 | 47,454,264 |
| R5 | 15,000 | 15,000 | 0.1 | 15.0 | 48,607,659 |
| R6 | 15,000 | 15,000 | 0.2 | 15.0 | 50,842,096 |
| R7 | 15,000 | 15,000 | 0.3 | 15.0 | 59,095,199 |
| R8 | 15,000 | 15,000 | 0.4 | 15.0 | 78,740,332 |
| R9 | 15,000 | 15,000 | 0.5 | 15.0 | 113,036,674 |
| R10 | 15,000 | 5,000 | 0.0 | 15.0 | 48,144,714 |
| R11 | 15,000 | 5,000 | 0.1 | 15.0 | 49,342,934 |
| R12 | 15,000 | 5,000 | 0.2 | 15.0 | 51,632,063 |
| R13 | 15,000 | 5,000 | 0.3 | 15.0 | 60,078,887 |
| R14 | 15,000 | 5,000 | 0.4 | 15.0 | 79,922,978 |
| R15 | 15,000 | 5,000 | 0.5 | 15.0 | 114,427,451 |
| R16 | 5,000 | 5,000 | 0.0 | 15.0 | 61,940,056 |
| R17 | 5,000 | 5,000 | 0.1 | 15.0 | 63,158,595 |
| R18 | 5,000 | 5,000 | 0.2 | 15.0 | 75,388,360 |
| R19 | 5,000 | 5,000 | 0.3 | 15.0 | 95,312,998 |
| R20 | 5,000 | 5,000 | 0.4 | 15.0 | 140,847,143 |
| R21 | 5,000 | 5,000 | 0.5 | 15.0 | 281,788,929 |
| R22 | 5,000 | 15,000 | 0.0 | 15.0 | 61,372,548 |
| R23 | 5,000 | 15,000 | 0.1 | 15.0 | 62,510,028 |
| R24 | 5,000 | 15,000 | 0.2 | 15.0 | 74,585,276 |
| R25 | 5,000 | 15,000 | 0.3 | 15.0 | 94,273,784 |
| R26 | 5,000 | 15,000 | 0.4 | 15.0 | 139,741,687 |
| R27 | 5,000 | 15,000 | 0.5 | 15.0 | 279,936,469 |
| R28[a] | 15,000 | 15,000 | 0.0 | 13.5 | 40,708,326 |
| R29[b] | 15,000 | 15,000 | 0.0 | 15.0 | 42,819,071 |
| R30[c] | 15,000 | 15,000 | 0.0 | 15.0 | 237,005,179 |
| R31[d] | 15,000 | 15,000 | 0.0 | 15.0 | 56,837,120 |
| R32[e] | 15,000 | 5,000 | 0.0 | 15.0 | 48,144,714 |
| R33[f] | 15,000 | 5,000 | 0.0 | 15.0 | 46,052,892 |
| R34[g] | 15,000 | 15,000 | 0.0 | 15.0 | 172,355,190 |
| R35[h] | 15,000 | 15,000 | 0.0 | 15.0 | 97,796,754 |

[a] reduce TC2 by 10%, i.e. from $15/ton mile to $13.5/ton mile
[b] increase paper price by 10% and see if recycling rate increases
[c] ban aluminum
[d] uniform material prices set at average
[e] base run for R32, R33 comparisons
[f] increase steel price by $100 for time periods 7, 8, and 9
[g] ban newspaper
[h] increase newspaper tipping fee from $15 per ton to $150 per ton

## Table 6. Effect of Fluctuating (R4) vs. Uniform (R31) Prices on Inventory

| Run / Obj. Val. | Qtr | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4 | P | 0 | 0 | 64 | 1,126 | 7,456 | 4,885 | 0 | 0 | 8,094 | 0 | 0 | 0 |
| Obj | G | 0 | 0 | 0 | 168 | 742 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $47M | S | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Al | 38 | 75 | 113 | 353 | 189 | 1,517 | 2,496 | 2,931 | 0 | 0 | 0 | 0 |
| | Pl | 0 | 0 | 0 | 0 | 0 | 0 | 1,056 | 711 | 0 | 0 | 0 | 0 |
| 31 | P | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Obj | G | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $57M | S | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Al | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Pl | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

P – Paper, G – Glass, S – Steel, Al – Aluminum, Pl – Plastics (in tons)

## Table 7a. Comparison of No Recycling, Recycling w/o Inventory and Recycling w/ Inventory: *Inventory Only*

| Run / Obj. Val. | Qtr | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1<br>Obj.<br>$81M | P | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | G | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | S | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Al | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Pl | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2<br>Obj.<br>$42M | P | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | G | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | S | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Al | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Pl | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3<br>Obj.<br>$38M | P | 0 | 0 | 6,686 | 21,515 | 66,480 | 66,918 | 0 | 0 | 76,576 | 0 | 0 | 0 |
| | G | 0 | 0 | 0 | 2,345 | 9,457 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | S | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Al | 237 | 475 | 714 | 1,243 | 2,849 | 4,566 | 6,642 | 8,543 | 0 | 0 | 0 | 0 |
| | Pl | 0 | 0 | 0 | 0 | 0 | 0 | 13,492 | 21,950 | 0 | 0 | 0 | 0 |

P – Paper, G – Glass, S – Steel, Al – Aluminum, Pl – Plastics (in tons)

## Table 7b. Comparison of No Recycling, Recycling w/o Inventory and Recycling w/ Inventory: *Recycled* (Including Inventory and Sale of) *Materials*

| **Run / Obj. Val.** | **Qtr** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | P | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Obj | G | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $81M | S | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Al | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Pl | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | P | 6,646 | 6,666 | 6,686 | 6,706 | 6,726 | 45,870 | 53,068 | 53,227 | 88,682 | 92,885 | 59,146 | 48,937 |
| Obj | G | 1,051 | 1,054 | 1,058 | 1,061 | 1,064 | 7,255 | 8,393 | 8,419 | 14,026 | 14,691 | 9,355 | 7,740 |
| $42M | S | 949 | 952 | 955 | 958 | 961 | 6,553 | 7,581 | 7,604 | 12,669 | 13,269 | 8,449 | 6,991 |
| | Al | 237 | 238 | 239 | 240 | 240 | 1,638 | 1,895 | 1,901 | 3,167 | 3,317 | 2,112 | 1,748 |
| | Pl | 1,543 | 1,548 | 1,552 | 1,557 | 1,561 | 10,648 | 12,319 | 12,356 | 20,587 | 21,563 | 13,730 | 11,360 |
| 3 | P | 6,646 | 6,666 | 6,686 | 14,830 | 44,965 | 48,065 | 58,122 | 53,227 | 90,442 | 92,885 | 59,146 | 48,937 |
| Obj | G | 1,051 | 1,054 | 1,058 | 2,346 | 7,112 | 7,602 | 9,193 | 8,419 | 14,305 | 14,691 | 9,355 | 7,740 |
| $38M | S | 949 | 952 | 955 | 2,119 | 6,424 | 6,866 | 8,303 | 7,604 | 12,920 | 13,269 | 8,449 | 6,991 |
| | Al | 237 | 238 | 239 | 530 | 1,606 | 1,717 | 2,076 | 1,901 | 3,230 | 3,317 | 2,112 | 1,748 |
| | Pl | 1,543 | 1,548 | 1,552 | 3,443 | 10,438 | 11,158 | 13,493 | 12,356 | 20,996 | 21,563 | 13,730 | 11,360 |

P – Paper, G – Glass, S – Steel, Al – Aluminum, Pl – Plastics (in tons)

## Table 8. Sensitivity of Recycling Rate to Unit Transportation Cost

| Qtr | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **R4** | 0.04 | 0.04 | 0.04 | 0.04 | 0.06 | 0.22 | 0.27 | 0.25 | 0.44 | 0.47 | 0.28 | 0.23 |
| **R28** | 0.04 | 0.04 | 0.04 | 0.04 | 0.06 | 0.24 | 0.32 | 0.28 | 0.47 | 0.47 | 0.32 | 0.23 |

## Table 9. Effect of a Price Increase in Paper on the Quarterly Recycling Rate

| Qtr | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | $MM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **R4** | | | | | | | | | | | | | |
| P | 0.03 | 0.03 | 0.03 | 0.03 | 0.04 | 0.14 | 0.17 | 0.16 | 0.29 | 0.31 | 0.18 | 0.15 | **47.5** |
| **R28** | | | | | | | | | | | | | |
| P | 0.03 | 0.03 | 0.03 | 0.03 | 0.04 | 0.15 | 0.22 | 0.18 | 0.31 | 0.31 | 0.21 | 0.15 | **40.7** |
| **R29** | | | | | | | | | | | | | |
| P | 0.03 | 0.03 | 0.03 | 0.03 | 0.04 | 0.15 | 0.22 | 0.17 | 0.29 | 0.31 | 0.20 | 0.15 | **42.8** |

P: Paper

## Table 10a. R32 Inventory Portfolio with Historical Steel Prices

| Qtr | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | $MM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **R32** | | | | | | | | | | | | | 48.1 |
| Paper | 0 | 0 | 0 | 0 | 2,334 | 662 | 0 | 0 | 2,698 | 0 | 0 | 0 | |
| Glass | 0 | 0 | 0 | 0 | 135 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| Steel | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| Aluminum | 0 | 38 | 75 | 315 | 151 | 963 | 1,078 | 1,117 | 0 | 0 | 0 | 0 | |
| Plastics | 0 | 0 | 0 | 0 | 0 | 0 | 157 | 126 | 0 | 0 | 0 | 0 | |

## Table 10b. R33 Inventory Portfolio with Inflated Steel Prices in Quarters 7, 8, and 9

| Qtr | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | $MM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **R33** | | | | | | | | | | | | | 46.1 |
| Paper | 0 | 0 | 0 | 0 | 2,228 | 263 | 0 | 0 | 2,698 | 0 | 0 | 0 | |
| Glass | 0 | 0 | 0 | 0 | 135 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| Steel | 0 | 0 | 0 | 152 | 304 | 2,584 | 0 | 0 | 0 | 0 | 0 | 0 | |
| Aluminum | 0 | 0 | 4 | 244 | 80 | 118 | 1,122 | 1,276 | 0 | 0 | 0 | 0 | |
| Plastics | 0 | 0 | 0 | 0 | 0 | 0 | 122 | 0 | 0 | 0 | 0 | 0 | |

## Table 11a. Effect of a Landfill Ban on Paper

| Qtr | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | $MM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **R34** | | | | | | | | | | | | | 172 |
| Paper | 0.39 | 0.39 | 0.39 | 0.39 | 0.39 | 0.39 | 0.39 | 0.39 | 0.39 | 0.39 | 0.39 | 0.39 | |
| Glass | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | |
| Steel | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | |
| Aluminum | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | |
| Plastics | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | 0.07 | |

## Table 11b. Effect of a Landfill Ban on Aluminum

| Qtr | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | $MM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **R30** | | | | | | | | | | | | | 237 |
| Paper | 0.39 | 0.39 | 0.39 | 0.39 | 0.39 | 0.39 | 0.39 | 0.39 | 0.39 | 0.39 | 0.39 | 0.39 | |
| Glass | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | |
| Steel | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | |
| Aluminum | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | |
| Plastics | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | 0.09 | |

## Table 12. Effect of a Landfill Ban and Graduated Tipping Fee on the Newspaper Recycling Rate

| Qtr | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | $MM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **R4** | 0.03 | 0.03 | 0.03 | 0.03 | 0.04 | 0.14 | 0.17 | 0.16 | 0.29 | 0.31 | 0.18 | 0.15 | 47 |
| **R34** | 0.39 | 0.39 | 0.39 | 0.39 | 0.39 | 0.39 | 0.39 | 0.39 | 0.39 | 0.39 | 0.39 | 0.39 | 172 |
| **R35** | 0.15 | 0.15 | 0.15 | 0.15 | 0.15 | 0.22 | 0.27 | 0.26 | 0.31 | 0.32 | 0.30 | 0.21 | 98 |