A flexible inventory model for municipal solid waste recycling

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Abstract

State laws mandate the recycling of municipal solid waste (MSW) across most of the United States. In order to comply, municipalities recycle quotas of materials, generally 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 that 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 $1.28 per ton of MSW generated as 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, including reducing the transportation cost for recyclables, supporting the market price of selected secondary materials, and landfill bans on selected materials. Our proposed model may also be used to investigate the effect of market price changes on the portfolio of materials held in inventory for recycling.

Keywords: Municipal solid waste; Recycling; Inventory; Optimization

1. Introduction

State laws mandate the recycling of municipal solid waste (MSW) across most of the United States. In order to comply, municipalities recycle quotas of materials, generally without regard to fluctuating prices. The prices of recycled materials (also called secondary materials) tend to track...
Nomenclature

Definition of sets

\( i \) waste generator
\( j \) material recycling facility (MRF)
\( l \) landfill site
\( m \) types of secondary materials, including paper, glass, steel, aluminum, plastics
\( t \) time period, quarter

Definition of variables

\( A_j \) warehouse capital cost, $/quarter
\( (A/P, r, 80) \) capital recovery factor
\( \text{BAN}_m \) 0 or 1 parameter for banning material \( m \)
\( \text{BIGM} \) a very large number
\( \text{CC}_m \) processing cost for material, \( m \), in $/ton
\( \text{COMP}_m \) waste stream composition for material \( m \), %
\( \text{CAPV} \) warehouse capacity (volume), cubic yards
\( \text{CAPW} \) landfill capacity, tons/quarter
\( D \) distance, mile
\( G \) solid waste generation growth rate, %/quarter
\( G_{i0} \) solid waste generation at generator \( i \) at quarter 0, tons
\( G_{it} \) solid waste generation at site \( l \) and time \( t \), tons
\( \text{INV}_{mjlt} \) inventory of material \( m \) at \( j \) and time \( t \), tons
\( \text{LF}_{mjlt} \) material \( m \) recycled at \( j \) then sent to \( l \) at time \( t \), tons
\( \text{MINTRR} \) minimum total recycling rate required, %
\( \text{MINMRR}_m \) minimum recycling rate for material \( m \), %
\( \text{MP}_{mt} \) market price for second material \( m \) in time \( t \), $/ton
\( \text{MRFC}_t \) total MRF sorting and processing cost in $/quarter
\( \text{MRR}_{mjt} \) material \( m \) recycling rate at time \( t \), %
\( \text{NONPAPER}_{jt} \) recyclable exclude paper received at \( j \) at time \( t \), tons
\( \text{NR}_{ilt} \) non-recyclable waste flow between \( i \) and \( l \) at time \( t \), tons
\( \text{PAPER}_{jt} \) recyclable paper received at \( j \) at time \( t \), tons
\( \text{PROG} \) 1, if there is a recycling program; 0; otherwise
\( r \) discount rate, %
\( R_{1ijt} \) recyclable but not recycled flow between \( i \) and \( l \) at time \( t \), tons
\( R_{2jlt} \) recyclable flow between \( i \) and \( j \) at time \( t \), tons
\( \text{RECYCLE}_{mjlt} \) material \( m \) recycled at \( j \) stored at warehouse at time \( t \), tons
\( \text{SC} \) MRF sorting cost, $/ton
\( \text{SE}_{mjt} \) material \( m \) sold at time \( t \), $/ton
\( \text{SORT}_{jt} \) recyclable material sorted at \( j \) at time \( t \), tons
\( \text{SORTCAP}_j \) processing capacity at MRF \( j \), tons/quarter
overall demand for manufactured goods and, therefore, be quite volatile. Currently, municipal recyclers do not hold their materials in storage in order to speculate on price. Instead, they sell their stock to dealers at prevailing market prices or at set prices for a given contract period. This practice prevents municipalities from maximizing the revenues they could get if they sold each recycled material at its highest market price in a given operating cycle of say, 6 months to 1 year.

The inventory concept is simple. Municipalities incur costs, $DC$, to build and operate warehouses to store their recyclables. They earn extra revenue, $DR$, from the strategic sale of recyclables. The investment in an inventory system is feasible if the net present value of ($DR$–$DC$) is positive for a specified planning horizon and discount rate. The strategy is to release materials from inventory at their highest estimated prices within the operating cycle.

The inventory method has two main limitations; however, the size of the investment required for warehouses and uncertainty about future prices for recycled materials. This paper directly addresses the first limitation. Using historical data on recycled materials prices, this study demonstrates that the proposed inventory system can significantly reduce MSW recycling cost to municipalities over a 3-year planning horizon. A model to support decision making under price uncertainty is being developed.

2. Literature review

Integrated waste management establishes a hierarchy for MSW that places a greater preference on waste reduction, reuse, and recycling, than on landfill and incineration [1]. Mathematical
models can greatly assist municipalities in selecting the appropriate mix of technologies and recycling strategies for managing their MSW within the integrated waste management framework. The available mathematical models include optimization models, such as linear programming (LP), mixed-integer linear programming (MILP), nonlinear programming (NLP), dynamic programming (DP), and multi-objective programming (MOP). They also include simulation models, such as Excel spreadsheets.

Lund [2] developed an LP approach for optimal material recycling and landfill utilization. Lund et al. [3] used an LP model in the design of a centralized material-recovery facility (CMRF). Their formulation considers all components of cost for a CMRF and incorporates the revenue from recyclables into the objective function. In this model, the objective minimized the total cost of recycling. They consider several sorting stages for commingled and presorted input streams of recyclables. However, they do not consider the case of storage to capitalize on fluctuating prices for secondary materials. Furthermore, Lund et al. [2] used a static model of secondary materials prices, while the formulation in the current study uses a dynamic model of materials prices that vary over the planning period.

Masui et al. [4] used an economic input–output model to investigate recycling as a mix of waste management options under different environmental and economic conditions. This model showed that the recovery benefit of recycling activities can make it an attractive alternative to incineration and landfill under conditions of severe space constraints. Van der Laan et al. [5] employed an inventory model to compare the options of recycling or disposal of used products. This model does not address the issues of secondary materials storage and prices, but it does demonstrate the concept of inventory as a way to influence the cost of waste management options. Starreveld and Van Ireland [6] used a materials balance optimization model to evaluate different policies for the recycling of plastics. These authors consider the case of a charge on disposal of plastics at landfills or incinerators but do not specifically consider the issues of storage and strategic sales to maximize revenues from fluctuating market prices.

Baetz and Neebe [7] developed an MILP model capable of determining optimal recycling program development levels for individual recyclable materials within an integrated waste management system [7]. Chang et al. [8] constructed 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. Barlishen and Baetz [9] developed a decision support system for MSW management planning based on an MILP approach. Their comprehensive model covers all aspects of MSW program planning from waste generation, waste reduction/reuse, recycling, composting, and various disposal options.

Fiorucci et al. [10] also developed a decision support system for overall MSW management for municipalities. They model the problem as a constrained nonlinear optimization structure that seeks to minimize total cost, including recycling, transportation, and maintenance costs. Baetz [11] applied a DP model to determine the optimal capacity expansion pattern for waste-to-energy and landfill facilities. Perlack and Willis [12] used an MOP model for the planning of a sludge disposal system. Hoshino et al. [13] constructed a multi-objective goal programming model to maximize the profitable recycling rate from a recycle-oriented manufacturing process. Again, the challenge of fluctuating market prices for a mix of secondary materials was not addressed in their optimization.
Other researchers have used simulation approaches to study the effectiveness of various recycling policies. For example, Palmer et al. [14] simulated three price-based policies for solid waste reduction—deposit/refunds, advance disposal fees, and recycling subsidies. Their results indicate that deposit/refund is the least costly of the policies. Anex et al. [15] developed a spreadsheet-based simulation package for MSW systems called GIGO. This software allows planners to simulate the effects of policy and technology changes on the performance of the MSW system. GIGO permits the planner to evaluate changes to the entire MSW system or to individual components, such as recycling. GIGO incorporates secondary materials prices into its analysis but does not consider the strategy of storing recyclables for sale at high prices in order to boost recycling revenue.

We have developed an NLP 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 a decision maker to develop an optimal recycling strategy to maximize revenue when material market prices fluctuate and are given exogenously. Our model adds the new concept of an inventory warehouse to the recycling literature and expands the range of options available to municipalities seeking to control recycling program costs. Municipalities may also employ this model to aid in decision making about warehouse investment and strategic considerations, such as:

- the location and the size of warehouses;
- which materials to recycle, what fraction of them, and when;
- 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 assumes that all the inventory warehouses are built at the beginning of the 3-year planning horizon. A mixed-integer nonlinear programming model (MINLP) to answer the time-to-invest question is being developed as future work.

3. System configuration

Fig. 1 shows the diagram of a generic MSW recycling system. We assume that the MSW is collected at curbside and that the system includes waste generators, material recycling facilities (MRFs), warehouses, and landfill sites. No transfer station or waste-to-energy facility is considered in the current version of the model. Collected non-recyclable (NR) solid waste is sent to the landfill directly. Recyclable MSW (assumed to be a mixture of paper, glass, steel, aluminum, and plastics) is collected separately and sent to MRFs for sorting and processing. The model assumes that paper is separated from the rest of the recyclables immediately upon arrival at the MRF. The recycled paper can then be sent to a warehouse, landfill or sold on the recycled paper market. The rest of the recyclables are then sent to the sorting facility, where glass, steel, aluminum, and plastics are separated. The separated materials move to a warehouse for storage or are sold on the secondary materials market. Recyclables may be sent to a landfill if
the quantity of non-paper recyclable waste is larger than the MRFs processing capacity or that of the warehouse, and there is no demand for the material on the secondary materials market. The recycling model presented in this paper assumes that the warehouses are collocated with MRFs. This assumption can be relaxed if information on the location of potential warehouses is available.

4. Model caveat

The goal of this research is to demonstrate the potential of an inventory warehouse to reduce the net present value of an 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. Furthermore, the total quantity of MSW generation will increase at 1% 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.
- 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 period. Some warehouses would not start banking at the beginning of the planning time period.
- Quarterly cash flows.
5. Recycling systems model formulation

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

5.1. Objective function

The objective function of this MSW recycling model seeks to minimize the discounted net system costs over a 3-year planning horizon. The model looks at the costs of MSW transportation from generators and MRFs to landfill sites ($\text{TRAN}_1^t$); recycled materials transportation from MSW generators to MRFs ($\text{TRAN}_2^t$); total recycled materials sorting ($\text{SORT}_{jt}$) and processing ($\text{RECYCLE}_{mjt} \times \text{CC}_m$); tipping fee ($\text{TFEE}_t$) at all landfill sites, and capital and operation and management (O&M) of the secondary material inventory warehouses. The first four cost components are expressed in Eqs. (1)–(4), respectively. Eq. (4) deserves special attention. The model allows different tipping fees based on the components in the waste stream in order to investigate the possibility of increasing the recycling rate for specific materials by charging higher landfill tipping fees. This, along with the costs for the warehouse, will be discussed in a later section.

\begin{align}
\text{TRAN}_1^t &= \sum_i \sum_l (\text{NR}_{ilt} + \text{R1}_{ilt}) D_{jl} + \sum_m \sum_l \sum_l \text{LF}_{mjit} D_{jl} + \sum_j \sum_l \text{UNSORT}_{jlt} D_{jl} \left[ TC_1 \right] \forall t, \ (1) \\
\text{TRAN}_2^t &= \sum_l \sum_j \text{R2}_{ijt} D_{ij} \left[ TC_2 \right] \forall t, \ (2) \\
\text{MRFC}_t &= \sum_j \text{SORT}_{jt} \times \text{SC} + \sum_j \sum_m \text{RECYCLE}_{mjt} \times \text{CC}_m \forall t, \ (3) \\
\text{TFEE}_t &= \sum_l \sum_i (\text{NR}_{ilt} \times \text{TFEE}) + \sum_l \sum_j \sum_m (\text{LF}_{mjit} \times \text{TFEE}_m) \\
&\quad + \left( \sum_l \sum_i \text{R1}_{ilt} \left( \sum_m (\text{COMP}_m \times \text{TFEE}_m) \right) + \left( 1 - \sum_m \text{COMP}_m \right) \times \text{TFEE} \right) \\
&\quad + \left( \sum_j \sum_l \text{UNSORT}_{jlt} \right) \sum_m \frac{\text{COMP}_m \times \text{TFEE}_m}{\sum_m \text{COMP}_m} \forall t. \ (4)
\end{align}

5.1.1. Capital and O&M costs at inventory warehouse

The development of a capital cost function for a recycling inventory warehouse takes into account many factors, including the automation level, storage and handling equipment, and
regional factors such as land prices [16]. In our model, we assume the inventory warehouse cost model shown in Eq. (5) and 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. The model also assumes that \(b\) has value between 0 and 1, which means the capital cost shows an economy of scale

\[
a_j(CAPV_j)^b_t \quad \forall t. \tag{5}
\]

As mentioned earlier, the model does not address the issue of when to invest in a warehouse. It assumes that all necessary warehouses are built at the beginning of the planning horizon and further that every warehouse has a 20-year lifetime. However, costs, prices, and revenues for the recycling system will be analyzed on a 3-year basis. Using a fixed quarterly interest rate \(r\), the amortized quarterly capital cost for each warehouse \((A_j)\) is expressed by Eq. (6) and the amortized quarterly capital cost for all warehouses in the system \((WCC_t)\) is given by Eq. (7)

\[
A_j = a_j(CAPV_j)^b(A/P, r, 80) \quad \forall j, \tag{6}
\]

\[
WCC_t = \sum_j A_j \quad \forall t. \tag{7}
\]

We assume that the O&M cost of an inventory warehouse at 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 at specific time period \((WOM_t)\) is expressed in Eq. (8), where \(C_j\) and \(d_j\) are site-specific parameters in the O&M cost function and \(VINV_j\) is the total volume of material in inventory at time, \(t\). For example, a rural area may have lower labor costs

\[
WOM_t = \sum_j c_j(VINV_j)^{d_j} \quad \forall t. \tag{8}
\]

Eq. (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 \((MP_{mt})\)

\[
TR_t = \sum_j \sum_m SE_{mjt} MP_{mt} \quad \forall t. \tag{9}
\]

The objective function is to minimize the discounted cash flow of all systems costs minus revenue, over the planning horizon of 3 years. The complete objective function is expressed in Eq. (10), where \(r\) is the quarterly discount rate

\[
Z = \sum_t \frac{TR_t + \sum_j \sum_m SE_{mjt} MP_{mt} + TR_t + WOM_t + WCC_t}{(1 + r)^t}. \tag{10}
\]

5.2. Constraint set

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

Assume that the generation of MSW in any quarter, \( t \), denoted by \( G_{i,t} \), increases at a fixed growth rate \( g \), given by Eq. (11). For simplicity, further assume that the composition of recyclables in the MSW stream is also fixed over the entire planning horizon. Consider the MSW stream to include NR materials, along with five types of recyclable materials: paper, glass, steel, aluminum, and plastics. These assumptions can be relaxed easily depending on data availability for specific cases

\[
G_{i,t} = G_{i0}(1 + g)^t \quad \forall i, t. \tag{11}
\]

5.2.2. 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 \( i (G_{i,t}) \) includes three different categories; NR materials, recyclable materials that are not recycled \((R1)\) due to economic or other reasons, and material that are actually recycled \((R2)\). This is given by Eq. (12). The first and the second waste categories are sent to landfills and the third is sent to MRFs.

Eqs. (13) and (14) provide tighter bounds for material flow variables. Eq. (13) says that the flow of NRs sent from municipality \( i \) to all landfill sites \( l \) \((NR_{i,lt})\) must equal all NR generated from \( i \). Eq. (14) says that recyclable but not recycled \((R1_{i,lt})\) plus actually recycled materials \((R2_{i,lt})\) should equal to all recyclable materials generated from \( i \)

\[
G_{i,t} = \sum_l NR_{i,lt} + \sum_j R1_{i,lt} + \sum_j R2_{i,jt} \quad \forall i, t, \tag{12}
\]

\[
\sum_l NR_{i,lt} = G_{i,t} \left(1 - \sum_m COMP_m\right) \quad \forall i, t, \tag{13}
\]

\[
\sum_l R1_{i,lt} + \sum_j R2_{i,jt} = G_{i,t} \sum_m COMP_m \quad \forall i, t. \tag{14}
\]

5.2.3. 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 that 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 \( R2 \) 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 that 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. Then \( R2 \) does not have any upper bound, and the constraint becomes redundant

\[
\sum_i \sum_j R2_{i,jt} \leq BIGM \cdot PROG. \tag{15}
\]
5.2.4. Paper received

We assume that 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, the model tracks the paper flow separately. The paper for recycling is stored, sold, or sent to a landfill.\(^1\) Since we assume that the composition of recyclable materials from all generators is the same, the total amount of paper received at a specific MRFs \(j\) and time period \(t\), can be expressed using Eq. (16)

\[
PAPER_{jt} = \sum_i R_{2ijt} \text{COMP}_{PAPER} / \sum_m \text{COMP}_m \quad \forall j, t. \tag{16}
\]

Eq. (17) says that the inventory of paper at specific MRFs, \(j\), at time period, \(t\), is equal to the previous inventory plus the paper received for the current time period subtracting the paper sold and sent to landfill

\[
INV_{PAPER_{jt}} = INV_{PAPER_{jt-1}} + PAPER_{jt} + \sum_l LF_{PAPER_{jlt}} - SEPAPER_{jt} \quad \forall j, t. \tag{17}
\]

Eq. (18) defines (RECYCLE\(_{PAPER_{jt}}\)) the amount of paper recycled at an MRF \(j\), during time period \(t\). Paper recycled at MRFs, \(j\), 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, such that it increases the inventory in the warehouse or it can be sold on the secondary material market

\[
RECYCLE_{PAPER_{jt}} = INV_{PAPER_{jt}} - INV_{PAPER_{jt-1}} + SEPAPER_{jt}
\]

\[= PAPER_{jt} - \sum_l LF_{PAPER_{jlt}}. \tag{18}\]

5.2.5. Non-paper recyclable material received

Eq. (19) is the quantity of the non-paper recyclable waste stream, which includes glass, steel, aluminum and plastics, received at MRFs, \(j\)

\[
NONPAPER_{jt} = \sum_i R_{2ijt} - PAPER_{jt} \quad \forall j, t. \tag{19}
\]

5.2.6. Mass balance at sorting facility

If non-paper 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. Eq. (20) says that the non-paper 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 that the amount of waste that gets sorted is bounded above by the sorting capacity at each MRF, \(j\)

\[
NONPAPER_{jt} = \sum_l UNSORT_{jlt} + SORT_{jt} \quad \forall j, t, \tag{20}
\]

\[
SORT_{jt} \leq SORT\text{CAP}_j. \tag{21}
\]

\(^1\)Sending recycled material to a landfill is a last resort. This option incurs the transportation cost and tipping fee at the landfill. It is better to first try to store the material, sell it at the going market price, or even pay someone to take it at a cost that is less than that of disposal via landfill.
5.2.7. Recycling constraint

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

\[
\text{RECYCLE}_{mjt} = (\text{SORT}_{jt} \times \text{COMP}_m) - \sum_{m \notin \text{PAPER}} \text{COMP}_m - \sum_l \text{LF}_{mj} \quad \forall m \{\text{PAPER}, j, t \}
\]

\[
= \text{INV}_{mjt} - \text{INV}_{mjt-1} + \text{SE}_{mjt}.
\]

(22)

5.2.8. Capacity constraint

The volume of all secondary materials in inventory at an MRF 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 EPA (1997), we derive the volume of recycled material in the warehouse. We add a 100% factor for working space. Eq. (23) is the total space required at warehouse, \(j\), during time period, \(t\). Constraint (24) says that the total space at warehouse, \(j\), during any time period (taken to be a quarter) is bounded above by its capacity. Thus, the total space requirement is the volume of inventory multiplied by two

\[
\text{VINV}_{jt} = \sum_m (\text{INV}_{mjt} \times \text{WT2VOL}_m)2.0 \quad \forall j, t,
\]

(23)

\[
\text{VINV}_{jt} \leq \text{CAPV}_j \quad \forall j, t.
\]

(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

\[
\sum_j \left( \sum_m \text{LF}_{mjlt} + \text{UNSORT}_{jt} \right) + \sum_i \text{NR}_{ilt} \leq \text{CAPW}_l \quad \forall l, t.
\]

(25)

5.2.9. 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. Eq. (26) defines the entire system’s recycling rate, for the quarterly time period, \(t\), for all materials. Eq. (27) does the same for and 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

\[
\text{TRR}_t = \frac{\sum_j \sum_m \text{RECYCLE}_{mjt}}{\sum_i G_{it}} \quad \forall t,
\]

(26)

\[
\text{MRR}_{mt} = \frac{\sum_j \text{RECYCLE}_{mjt}}{\sum_i G_{it}} \quad \forall m, t,
\]

(27)

\[
\text{TRR}_t \geq \text{MINTRR} \quad \forall t,
\]

(28)

\[
\text{MRR}_{mt} \geq \text{MINMRR}_m \quad \forall m, t.
\]

(29)
5.2.10. 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 it [17]. 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 of Eq. (30) for each individual recyclable material.

\[
\sum_{i} \sum_{l} R_{il}^{m} \text{COMP}_{m} + \sum_{j} \sum_{l} \text{UNSORT}_{jl}^{m} \left( \frac{\text{COMP}_{m}}{\sum_{m \neq \text{PAPER}} \text{COMP}_{m}} \right) + \sum_{j} \sum_{l} \text{LF}_{jlm} \leq \text{BIGM}(1 - \text{BAN}_{m}) \quad \forall \ m, \ t. \tag{30}
\]

The left-hand side (LHS) of this constraint accounts for the total material flow of material, \( m \), from all sources that are received at all landfills in the MSW system. \( \text{BAN}_{m} \) on the RHS of the constraint is a 0 or 1 parameter. When \( \text{BAN}_{m} \) is equal to 1, it means that material \( m \), is banned from all landfills in the system. \( \text{BAN}_{m} \) equal to 1 makes the RHS of the constraint 0 and forces the flow of material, \( m \), to be zero at all landfills, simulating a total ban on the material \( m \) at all landfills in the system. When \( \text{BAN}_{m} \) 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 the MINMRR\( m \) equal to the composition of material, \( m \), in the waste stream. This means recycling all of material, \( m \), and is equivalent to a landfill ban on \( m \). 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 and their associated cost are not included in this study.

The model is now complete. It is a nonlinear dynamic optimization model. An NLP solver, CONOPT, in GAMS is used to solve this model.

6. Case study

In this section, a hypothetical case study is presented to test the assumption that an inventory warehouse could result in lower net cost for recycling MSW and to examine other questions about recycling policy. In this case study, we simulated MSW management system based on the model of Alleghany County, Pennsylvania, and a hypothetical MRF. The Alleghany County system consists of 133 municipalities, 13 landfill sites, and nine MRFs. Data on the location, capacity, linear distances, transportation costs for MSW and recycled materials, and estimated MRF processing cost and tipping fee at landfill sites are derived from the 1993, 1994, and 1995 annual reports on MSW management from the Allegheny County Sanitary Authority [18]. In order to simplify the mass balances and materials flows for the model, we aggregated the 133 municipalities in the Alleghany County system into 26 pseudo municipal districts. The MSW generation and growth rates and the composition of MSW are from Franklin [19]. Compressed secondary
material weight-to-volume conversion factors are from EPA [1,20]. The market prices of secondary materials are from California integrated waste management study [21].

The total population of the municipalities selected was 360,000. At the starting rate of MSW generation of 4.1 pounds per person per day, the total generation of MSW in the first quarter was 67,265 tons per quarter. Using the MSW composition data presented in Table 1 resulted in a value of 15,000 tons per quarter of MSW for sorting, excluding paper, which we assume is not mixed with the other components of the recyclable waste stream.

6.1. Basic data

Table 2 provides the capacity information for the 13 landfills in Alleghany County.

6.2. MSW recycling system layout

The MSW system includes 26 municipal centers, nine MRFs, and 13 landfills and its system layout is shown in Fig. 2. The distance matrices among these facilities are calculated using straight-line distance measurements.

6.3. Secondary materials market prices

The market prices of secondary materials are obtained from California Integrated Waste Management Study [21]. Fig. 3 shows the time series of quarterly market prices for five different secondary materials.

6.4. Cost function parameters

Table 3 contains various cost function parameters used in this paper. The parameter, \( a \), is calculated using warehouse quick cost calculator at http://www.rsmeans.com/ [22]. The calculator gives cost per square feet. We converted it to square yards and assumed each warehouse is 6 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 does not include land cost.

<table>
<thead>
<tr>
<th>Item</th>
<th>Composition (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nonrecyclable</td>
<td>38.5</td>
</tr>
<tr>
<td>Paper</td>
<td>39.2</td>
</tr>
<tr>
<td>Glass</td>
<td>6.2</td>
</tr>
<tr>
<td>Steel</td>
<td>5.6</td>
</tr>
<tr>
<td>Aluminum</td>
<td>1.4</td>
</tr>
<tr>
<td>Plastics</td>
<td>9.1</td>
</tr>
</tbody>
</table>

Source: [19].
Table 2
Landfill capacity

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

Source: [18].

Fig. 2. MSW recycling system layout.

6.5. Other basic data

Table 1 contains the MSW composition by weight percentage. Table 4 provides the weight-to-volume conversation factor used in the case study.
7. Analysis results

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

- **Question 1:** Is an inventory warehouse justified in 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 an MSW recycling system?

![Graph showing quarterly time series of the secondary material market prices.](image-url)

**Fig. 3.** Quarterly time series of the secondary material market prices.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>$(\text{cubic yards})$</td>
<td>65.6</td>
</tr>
<tr>
<td>$b$</td>
<td></td>
<td>0.98</td>
</tr>
<tr>
<td>$c$</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>$d$</td>
<td></td>
<td>0.98</td>
</tr>
<tr>
<td>$g$</td>
<td>%/qtr</td>
<td>0.003</td>
</tr>
<tr>
<td>TC1</td>
<td>$/\text{ton/mile}$</td>
<td>0.85</td>
</tr>
<tr>
<td>TC2</td>
<td>$/\text{ton/mile}$</td>
<td>15</td>
</tr>
<tr>
<td>TFEE</td>
<td>$/\text{ton}$</td>
<td>15</td>
</tr>
<tr>
<td>SC</td>
<td>$/\text{ton}$</td>
<td>36.35</td>
</tr>
<tr>
<td>$r$</td>
<td>%/qtr</td>
<td>0.015</td>
</tr>
</tbody>
</table>
Table 4
Weight-to-volume conversion factor

<table>
<thead>
<tr>
<th>Item</th>
<th>Factor (cubic yards per ton)</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paper</td>
<td>2.78</td>
<td>Compacted newsprint</td>
</tr>
<tr>
<td>Glass</td>
<td>0.89</td>
<td>Mechanically crushed</td>
</tr>
<tr>
<td>Steel</td>
<td>2.35</td>
<td>Flattened steel cans</td>
</tr>
<tr>
<td>Aluminum</td>
<td>5.88</td>
<td>Flattened</td>
</tr>
<tr>
<td>Plastics</td>
<td>7.41</td>
<td>Whole compacted HDPE (dairy)</td>
</tr>
</tbody>
</table>

Sources: [1,20].

- **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 in stabilizing secondary materials prices and reducing 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 3 years, broken into quarterly operating periods. 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.

7.1. **Analysis 1: The necessity of inventory warehouse (R31 vs. R4)**

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 over the same period. Analysis 1 seeks to demonstrate that an inventory warehouse is needed only when the market prices of the secondary materials fluctuate. Analysis 1 examines the results of two runs, R4 and R31, summarized in Table 6. In R31, each material is assigned a uniform price based on the average of its actual prices over the 12 quarters used for the analysis. R4, which is used for comparison, employs the actual quarterly prices of each material.

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 over the 3-year period. On the contrary, when material prices fluctuate (R4), 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...
Table 5
Summary of analysis runs

<table>
<thead>
<tr>
<th>Run no.</th>
<th>Sorting (Tons/qtr)</th>
<th>Storage (yard³)</th>
<th>Minimum recycling (Rate req'd)</th>
<th>TC2 ($/ton mile)</th>
<th>Obj value ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>0</td>
<td>0</td>
<td>0.0</td>
<td>15.0</td>
<td>81,154,778</td>
</tr>
<tr>
<td>R2</td>
<td>1.50E+08</td>
<td>0</td>
<td>0.0</td>
<td>15.0</td>
<td>42,106,520</td>
</tr>
<tr>
<td>R3</td>
<td>1.50E+08</td>
<td>1.00E+06</td>
<td>0.0</td>
<td>15.0</td>
<td>37,623,892</td>
</tr>
<tr>
<td>R4</td>
<td>15,000</td>
<td>15,000</td>
<td>0.0</td>
<td>15.0</td>
<td>47,454,264</td>
</tr>
<tr>
<td>R5</td>
<td>15,000</td>
<td>15,000</td>
<td>0.1</td>
<td>15.0</td>
<td>48,607,659</td>
</tr>
<tr>
<td>R6</td>
<td>15,000</td>
<td>15,000</td>
<td>0.2</td>
<td>15.0</td>
<td>50,842,096</td>
</tr>
<tr>
<td>R7</td>
<td>15,000</td>
<td>15,000</td>
<td>0.3</td>
<td>15.0</td>
<td>59,095,199</td>
</tr>
<tr>
<td>R8</td>
<td>15,000</td>
<td>15,000</td>
<td>0.4</td>
<td>15.0</td>
<td>78,740,332</td>
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<tr>
<td>R9</td>
<td>15,000</td>
<td>15,000</td>
<td>0.5</td>
<td>15.0</td>
<td>113,036,674</td>
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<tr>
<td>R10</td>
<td>15,000</td>
<td>5000</td>
<td>0.0</td>
<td>15.0</td>
<td>48,144,714</td>
</tr>
<tr>
<td>R11</td>
<td>15,000</td>
<td>5000</td>
<td>0.1</td>
<td>15.0</td>
<td>49,342,934</td>
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<tr>
<td>R12</td>
<td>15,000</td>
<td>5000</td>
<td>0.2</td>
<td>15.0</td>
<td>51,632,063</td>
</tr>
<tr>
<td>R13</td>
<td>15,000</td>
<td>5000</td>
<td>0.3</td>
<td>15.0</td>
<td>60,078,887</td>
</tr>
<tr>
<td>R14</td>
<td>15,000</td>
<td>5000</td>
<td>0.4</td>
<td>15.0</td>
<td>79,922,978</td>
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<tr>
<td>R15</td>
<td>15,000</td>
<td>5000</td>
<td>0.5</td>
<td>15.0</td>
<td>114,427,451</td>
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<tr>
<td>R16</td>
<td>5000</td>
<td>5000</td>
<td>0.0</td>
<td>15.0</td>
<td>61,940,056</td>
</tr>
<tr>
<td>R17</td>
<td>5000</td>
<td>5000</td>
<td>0.1</td>
<td>15.0</td>
<td>63,158,595</td>
</tr>
<tr>
<td>R18</td>
<td>5000</td>
<td>5000</td>
<td>0.2</td>
<td>15.0</td>
<td>75,388,360</td>
</tr>
<tr>
<td>R19</td>
<td>5000</td>
<td>5000</td>
<td>0.3</td>
<td>15.0</td>
<td>95,312,998</td>
</tr>
<tr>
<td>R20</td>
<td>5000</td>
<td>5000</td>
<td>0.4</td>
<td>15.0</td>
<td>140,847,143</td>
</tr>
<tr>
<td>R21</td>
<td>5000</td>
<td>5000</td>
<td>0.5</td>
<td>15.0</td>
<td>281,788,929</td>
</tr>
<tr>
<td>R22</td>
<td>5000</td>
<td>15,000</td>
<td>0.0</td>
<td>15.0</td>
<td>61,372,548</td>
</tr>
<tr>
<td>R23</td>
<td>5000</td>
<td>15,000</td>
<td>0.1</td>
<td>15.0</td>
<td>62,510,028</td>
</tr>
<tr>
<td>R24</td>
<td>5000</td>
<td>15,000</td>
<td>0.2</td>
<td>15.0</td>
<td>74,585,276</td>
</tr>
<tr>
<td>R25</td>
<td>5000</td>
<td>15,000</td>
<td>0.3</td>
<td>15.0</td>
<td>94,273,784</td>
</tr>
<tr>
<td>R26</td>
<td>5000</td>
<td>15,000</td>
<td>0.4</td>
<td>15.0</td>
<td>139,741,687</td>
</tr>
<tr>
<td>R27</td>
<td>5000</td>
<td>15,000</td>
<td>0.5</td>
<td>15.0</td>
<td>279,936,469</td>
</tr>
<tr>
<td>R28a</td>
<td>15,000</td>
<td>15,000</td>
<td>0.0</td>
<td>13.5</td>
<td>40,708,326</td>
</tr>
<tr>
<td>R29b</td>
<td>15,000</td>
<td>15,000</td>
<td>0.0</td>
<td>15.0</td>
<td>42,819,071</td>
</tr>
<tr>
<td>R30c</td>
<td>15,000</td>
<td>15,000</td>
<td>0.0</td>
<td>15.0</td>
<td>237,005,179</td>
</tr>
<tr>
<td>R31d</td>
<td>15,000</td>
<td>15,000</td>
<td>0.0</td>
<td>15.0</td>
<td>56,837,120</td>
</tr>
<tr>
<td>R32e</td>
<td>15,000</td>
<td>5000</td>
<td>0.0</td>
<td>15.0</td>
<td>48,144,714</td>
</tr>
<tr>
<td>R33f</td>
<td>15,000</td>
<td>5000</td>
<td>0.0</td>
<td>15.0</td>
<td>46,052,892</td>
</tr>
<tr>
<td>R34g</td>
<td>15,000</td>
<td>15,000</td>
<td>0.0</td>
<td>15.0</td>
<td>172,355,190</td>
</tr>
<tr>
<td>R35h</td>
<td>15,000</td>
<td>15,000</td>
<td>0.0</td>
<td>15.0</td>
<td>97,796,754</td>
</tr>
</tbody>
</table>

aReduce TC2 by 10%, i.e. from $15/ton mile to $13.6/ton mile.
bIncrease paper price by 10% and see if the recycling rate increase.
cBan aluminum.
dUniform material prices set at average.
eBase run for R32, R33 comparisons.
fIncrease steel price by $100 for time periods 7–9.
gBan newspaper.
hIncrease newspaper tipping fee from $15 per ton to $150 per ton.
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 $57 million. However, when prices fluctuate and a warehouse of 15,000 yard$^3$ is added, the system cost drops to $47 million—a saving 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 over 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 the municipality’s entire inventory at the point of sale.

7.2. Analysis 2: Cost saving potential of recycling and inventory warehouse (R1, R2 and R3)

Our model demonstrates 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. The second analysis compares 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 over a 3-year cycle of secondary materials prices. The results of this study are summarized in Tables 7a and b. 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 presents the cost saving potential of recycling and inventory warehouse (R1, R2 and 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 3 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 3 years, representing a savings of $39 million or 48% over 3 years.

When warehousing capacity is added, the 3-year net system cost drops to $38 million, representing a 3-year savings of $43 million or 53% over the system with no recycling and a 3-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 3-year period, the addition of an inventory warehouse for recyclables is the least-cost alternative for managing MSW.

7.3. Analysis 3: MRFs sorting capacity and warehouse capacity (R4 and R27)

The previous analysis showed that recycling with warehouse capacity could be the lowest cost alternative for operating an 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 Fig. 4.

In R4–R9, the sorting capacity is set at 15,000 tons and the storage capacity at 15,000 yard$^3$ per quarter. This explains the legend “15 k, 15 k” in Fig. 4. The 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.

Table 7a
Comparison of no recycling, recycling without inventory, and recycling with inventory: inventory of materials (tons)

<table>
<thead>
<tr>
<th>Run no./obj. value</th>
<th>Mat. Quarter</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1/$81M</td>
<td>P</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>R2/$42M</td>
<td>P</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>R3/$38M</td>
<td>P</td>
<td>0</td>
<td>0</td>
<td>6686</td>
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Table 7b
Comparison of no recycling, recycling without inventory and recycling with inventory: recycled (including inventory and sale of) materials (tons)

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<td>6686</td>
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<td>6726</td>
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Fig. 4. MSW recycling cost curves.
In R10–R15, the effect of storage capacity is examined by reducing the storage capacity to 5000 yard³ per quarter at each MRF while keeping the sorting capacity fixed at 15,000 tons. 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 yard³. This is to be expected, as there is not sufficient 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–R21 sorting capacity is reduced to 5000 tons/quarter at each MRF and storage capacity is held at 5000 yard³. 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–R27 sorting capacity is held at 5000 tons/quarter at each MRF and storage capacity increased to 15,000 yard³. 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 are 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.

7.4. Analysis 4: Sensitivity of TC2 (R4–R28)

Based on the results of Analysis 3, it is natural to examine the sensitivity of total system cost to transportation cost, TC2. This comparison is made between R4 and R28. In R4 the materials transportation cost is $15 per ton per mile. In R28 the unit transportation cost is reduced 10% to $13.5 per ton per mile, resulting 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, which essentially means seeking ways to reduce collection costs. This simple sensitivity test is not sufficient to fully justify such a policy recommendation. However, it is sufficient basis for evaluation as future work.
7.5. Analysis 5: Increasing the recycling rate by subsidizing the recyclable material market price (R4 and R28, R29)

The analyses conducted in this study are based on perfect knowledge of the quarterly market price for recycled materials over a 3-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 and, furthermore, that when prices increase steadily, 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). Municipalities would sell only the amount that exceeded storage capacity in each quarter.

Analysis 5 compares the sensitivity of net system cost and recycling rate to constantly escalating market prices against that of reductions in the materials transportation cost, TC2. The comparison is based on an assumed 10% per quarter increase in the market price of recycled paper, the predominant constituent of the recycled materials stream. At 64% of all recyclable material, paper is four times more abundant than plastics, the next most prevalent material. The historical quarterly prices of the other recyclables are not affected.

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. Table 9 compares the quarterly recycling rates for R4, R28, and R29.

The price of paper is increased by 10% each quarter for 12 quarters. This represents an effective increase of 314% over the 3-year period. In spite of this large increase in the market price, the net cost of the recycling system is reduced by only 10%.

R28, discussed in Analysis 4, 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 is more effective at increasing the recycling rate than a steady increase in the price of paper, and that it lowers the net system cost by 14% compared to 10% for the increase in the price of paper. The full effect of price supports for recyclables cannot be fully explored by the simple assumption of a guaranteed increase for paper alone. Yet, this illustration shows that reducing the unit transportation cost of recyclables could be a more effective way to boost the recycling rate and to reduce the net cost of MSW recycling than price supports for recycled materials.

Table 9

<table>
<thead>
<tr>
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<th>Quarter</th>
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<td>0.04</td>
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<td>0.47</td>
<td>0.47</td>
<td>0.32</td>
<td>0.23</td>
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</table>
7.6. Analysis 6: Price effects on the portfolio of recyclables (R32 and R33)

When warehousing capacity is limited, expected 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 5000 cubic yards is assumed for reach MRF. The steel price is increased by $100 per ton consecutively for periods 7–9. In Tables 10a and b, respectively, the quantity of materials banked in the inventory warehouse before and after the price change is compared. As the base case results (R32) in Table 10a show, no steel is banked in the warehouse and its market price 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 7–9, steel is banked at period 4. Furthermore, the banking of paper and aluminum is reduced in periods 4–6 as the space is reserved for and substituted by more valuable steel.

7.7. 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. Tables 11a and b summarize the results for the paper (R34) and aluminum (R30) bans, respectively.

Since the 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 it 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 results in a sizeable increase in the net recycling system cost.

In the case of any recyclable material other than the paper, as illustrated by the example of aluminum, a landfill ban implies that the entire non-paper 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 landfill. 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 non-paper 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

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Table 10a  
R32 Inventory (tons) portfolio with historical steel prices

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Table 10b  
R33 inventory (tons) portfolio with inflated steel prices in quarters 7–9

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Table 11a  
Effect of a landfill ban on paper on recycling rate

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Table 11b  
Effect of a landfill ban on aluminum on recycling rate

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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 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 is not minimized.

One way to discourage landfilling of a given material without an outright 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/ton for all materials including newspaper and R35 a tenfold increase to $150/ton. R34 represents a landfill ban on newspaper.

The landfill ban on newspapers may increase the newspaper-recycling rate but it also increases the net systems cost from $47 million to $172 million over the 3-year period—an increase of 266%. Thus, from a cost perspective, the landfill ban would not be an attractive policy.

A discriminatory, tenfold increase in the tipping fee of newspaper would certainly discourage users from sending this material to the landfill. It 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—an increase of 109%—over 3 years. Though significantly less than the increase from a landfill ban, this is still a large percentage increase, and the municipality may want to weigh the benefit of a higher recycling rate against the higher cost associated with that policy.

8. Conclusion and recommendations

8.1. Conclusion

The goal of this paper was to determine whether the use of an inventory warehouse could reduce the net cost of recycling MSW. Using 3 years of quarterly prices for a portfolio of recyclable materials (paper, plastic, steel, aluminum, and glass), a nonlinear DP 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 seven policy questions related to the optimal strategy for managing the recycling system.

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.

For 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, since 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 was more effective at increasing the overall recycling rate than price supports for paper. This result suggests that municipalities interested in reducing recycling program costs and in 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 significantly contribute to increasing revenue in the future.

Finally, it was found that banning paper from landfills would increase the recycling rate for paper but would dramatically increase net system cost. If discriminatory tipping fees were used instead to discourage landfilling of paper, the recycling rate increases to about half that achieved by an outright ban but the net system cost increase, though significantly less than the increase from an outright ban. In a similar vein, banning other non-paper 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, net system cost increased from a base value of $47–$237 million, or 404%. Thus, if as we assume, all non-paper recyclable materials have to be sorted at MRFs in order to comply with a landfill ban on a single non-paper recyclable component, then the increase to net system cost can be prohibitive, even for a lucrative component like 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 can also be used to investigate infrastructure needs and conduct investment planning and analysis. For example, the optimal location and size of inventory warehouses within the municipality’s solid waste management program could be determined in order to minimize recycling system cost. If the cost function for each sorting facility is known, an optimal strategic plan for investing in future MRFs could be investigated.

8.2. Recommendations

The current model assumes all warehouses are built and available at the beginning of the overall planning period. However, this investment strategy may not minimize net system cost over the long term. If the market price is flat or decreasing, a warehouse to bank these materials would not be needed. This research has formulated an MINLP model that can answer the question of when to add warehouse capacity. However, this model has not yet been tested.
The current model is based on historical prices of secondary materials. Thus, while the model is dynamic, it is not predictive. The model is of limited practical value to decision makers in its present formulation since their materials storage strategy will be based on the predicted prices of materials in the near future. The study is considering use of a Bayesian estimator that provides an expected value prediction of future materials prices by quarter based on trends in historical quarterly prices.

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. We are now investigating how to obtain a robust warehouse design given uncertain future market prices.

Finally, the next step in the research may add 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.

In summary, the concept of warehousing recycled materials for sale at the best prices was demonstrated via an MINLP model. The model showed that warehousing and strategic sale of materials could reduce total recycling system cost. In addition, the model provides two significant recycling policy insights. The first insight is that reducing the transportation cost of recyclables can have a greater effect at reducing total recycling program cost than any price supports to boost secondary materials sales. The second insight is that though discriminatory tipping fees and outright bans on certain recyclables from landfills could increase the rate of recycling, these policies would result in large marginal costs likely to dwarf the benefit from the marginal increase in recycling rate. Because the model lacks predictive power in its present form, it is of little practical value to decision makers seeking to shape their recycling programs based on future prices for secondary material. Thus adding predictive capacity to the model has a high priority for future work in this study.

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