# A Post –Consumer Waste Management Model for Determining Optimal Levels of Recycling and Landfilling

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## Abstract

The present study examines the optimal recycling rate for municipal solid waste. First, an optimal control model is developed to account for the physical costs of recycling, the social costs of landfilling, and consumers' environmental preferences. Second, an optimal solution is simulated using waste disposal data from the Helsinki region in Finland. The benefits from recycling are included in the simulation using the results of a recent contingent valuation study. The results of the present research suggest that mandates for achieving 50 % recycling in municipalities are not far-fetched and are both economically and environmentally justified.

Keywords: landfilling, recycling, waste management, optimal control.

## 1 Introduction

Until recently, the least costly method for "treating" nonhazardous solid wastes has been to place them in landfills. Land, however, is becoming increasingly expensive in densely populated urban areas, making the opportunity cost of landfill space higher than before. Obviously, the area used for landfill is lost to other uses even long after the landfill is closed. The common not-in-my-backyard attitude makes it even more difficult to site landfills: opposition from residents and public hearing processes increase the fixed costs of building new landfills.

In addition to the difficulty in finding a suitable site for "storing" wastes, environmental effects, especially the problems caused by old landfills, have been heavily debated. Examples include the aesthetic deterioration of the environment, odors or even health risks via groundwater contamination. Water pollution may have serious consequences if, for example, due to improper landfill operation hazardous waste material gets mixed in with the otherwise nonhazardous solid waste stream.

In a landfill an additional waste unit that contributes to the accumulation of waste stock creates a social cost not typically accounted for in the prices of commodities produced and consumed. Waste management policy should, however, take into account such hidden costs. If all the shadow costs of landfills are properly considered, alternative methods of waste disposal may look more attractive than they have in the past. Consequently, source reduction has become a key word in waste management; the cheapest way to handle waste is not to create it. This has led both empirical and theoretical studies to investigate the potential of a proper pricing system to reduce waste.[1]

Source reduction, however, depends on the existence of commodities that generate less waste. To date, there is little - if any - information has been available on the costs of achieving higher levels of source reduction[2] at the household level by, for example, avoiding over-packaged products or searching for environmentally friendly goods. As an alternative, we include in our analysis a large-scale recycling program, since recycling is generally ranked as the second best alternative in waste management. Our study of

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[1] See, e.g., Beede and Bloom (1995), Hong, Adams and Love (1993), Morris and Holthausen (1994), Dinan (1993), Jenkins (1993).

[2] By "source reduction" it is meant here that waste is not created at all. Recycling is sometimes considered as a source reduction method, and data on recycling are more readily available.

recycling as a complementary waste management method is motivated by the notion that it seems to be widely accepted by the public. The same cannot be said for incineration, which is often listed as the third option in the waste management hierarchy. Incineration has faced public opposition mainly for environmental reasons: during burning, harmful residuals like dioxins and furans can be generated and the resulting ash may contain heavy metals.[3]

The model used includes only municipal solid waste, because it is possible to recycle a significant fraction of this waste type. The percentage of waste recycled can be raised by increasing the participation rate of households in recycling programs and by increasing the number of waste items that can be reused, such as paper, aluminum, glass, and plastic. These measures are not without cost, however. To induce participation, education and information are needed. Similarly, with more organized separation of waste, or with more recyclable items for recovery, the recycling system becomes more costly because of increasing collection and transportation costs. Since different waste items will be taken to different processing plants and have varying end uses, the scale economies are reduced vis-a-vis a situation where landfilling is the only treatment option. Finally, even though recycling is a politically attractive alternative, one should not go from one extreme, careless disposal, to another, prohibitively expensive recycling.[4] Therefore, we explicitly take into account the fact that recycling costs increase when more waste is recycled.

Clearly, there is an upper limit to how much waste can be recycled. Because 100% recycling is not possible, landfills are needed at least for nonrecyclable inorganic residues. The need for landfill space is implicitly determined given the amount of waste generated and the costs and constraints on recycling. Given the economic and environmental constraints discussed above, optimal recycling and landfill disposal paths over time are derived in a theoretical model which describes the waste accumulation phenomenon.[5]

In contrast to some previous studies, e.g., those by Hartwick et al. (1986), Wirl (1992) and Ready & Ready (1995), the present investigation includes more variables that are un-

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[3] See Eiswerth (1993) for a study of incineration as an alternative waste disposal method.

[4] For more critical views on waste disposal and recycling, and defense of garbage, see Alexander (1993).

[5] Because of the unavoidable and pervasive phenomenon of waste accumulation in landfills, there cannot be any steady state equilibrium for the waste stock except when the landfill is full or not used any more. This is in contrast to papers by Lusky (1976), Plourde (1972) and Smith (1972), in which it is implicitly assumed either that disposal in landfills would eliminate the problems of solid waste or that total recycling would be possible.

der the planner's control. When we are "extracting landfill space" (exhaustible resource), we are in fact "treating waste" for which we have an alternative technology available with different operation and environmental costs. The alternative technology, i.e., recycling efforts in our model, set an upper bound on the costs of using a landfill. The uncertain environmental effects of landfills are captured by an explicit damage function; these are assumed to affect, for example, the timing of when to close an old landfill and open a new one.

We will present a simulation model in which the optimal time paths for recycling rates of different waste items and waste stock accumulation are solved. This is an attempt at a quantification of optimal recycling and landfilling levels for the Helsinki region in Finland. The current amount of waste generated in the area is used as the initial value for the constant waste flow. The simulation model assumes that it is possible to control waste generation to a certain extent without extra costs; lower and upper bounds for variations in the waste flow are given. The results of a recent contingent valuation (CV) study are used to measure the non-market benefits from recycling. The study was conducted to analyze demand for alternative waste disposal services in Helsinki. The benefit measures obtained will be discussed in more detail in the simulation context. Estimates of the costs of recycling and operating landfills are also used.

Here, we take into account both private operating costs and social environmental costs of disposal methods in order to study how stringent the recycling mandates are which municipalities should impose. Of particular importance is the demand for recycling disposal services since it seems to reflect consumers' greening preferences and, consequently, "joy of recycling". The simulation results should still be taken with caution, since there are many kinds of uncertainties in the simulation data. Sensitivity analyses will be made to see how crucially the results change when chosen parameters or estimates are given different values.

## 2 The Model

Basically, we aim to find an optimal waste management plan by maximizing net benefits from disposal services subject to given technological constraints. We solve the problem for two subperiods only, but the optimization rule is extendable to several subperiods.

During each subperiod, a different landfill is used. The goal is to determine an optimal point of time to switch from using an old landfill to using a new one, the optimal size of which is implicitly determined.

Technically, we have two state variables: the space available in the landfill, $S$, and the waste stock, $W$, that accumulates in the landfill over time and may cause environmental damage years after the landfill has been closed. Assuming that extracting space (or storing waste in the landfill) equals the accumulation of waste over time, $dS/dt = -dW/dt = -L$, where $L$ is a control variable for the landfill use, there is thus really only one stock variable.

The direct environmental costs of using the landfill are captured by a landfill-specific scrap (terminal) value function. The scrap value includes the shut-down costs of a landfill, such as landscaping the area and planting trees, as well as potential future damage caused by the old landfill. Examples of such stochastic damages associated with old landfills could be a methane gas explosion or toxic leakage into groundwater. Hence, these environmental costs are entered into the objective functional.

We also need to take into account some benefits associated with recycling. In general, these benefits are mainly the raw material value of waste items and the value of recycling as a method of alleviating waste disposal problems. In the simulation exercise, the non-market benefits are captured by a consumer surplus or willingness to pay (WTP) measure derived from a contingent valuation (CV) study.[6] In the survey responses, recycling was generally seen as “an environmentally friendly disposal method which might also induce a change in wasteful consumption patterns”.

In the following, $i = 1, 2$ refers to periods one or two such that:

$$i = \begin{cases} 1 & \text{when } t \in [0, t_1] \\ 2 & \text{when } t \in [t_1, t_2] \end{cases}$$

The goal of the social planner is to maximize the present value of the discounted net

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[6] A CV survey was conducted to elicit people’s WTP for incineration and recycling disposal services in an effort to alleviate problems of declining landfill space in the Helsinki region in Finland (Huhtala (1994)). It is assumed that the consumer preferences revealed in the study do not change over the time considered in the simulation.

benefits from waste disposal services:

$$\max_{L_i, R_i,\, i=1,2} \quad \tilde{J} = \int_0^{t_1} e^{-\delta t} \left[\, B_1(R_1) - C_1^L(L_1) - C_1^R(R_1) \,\right] \, dt - F_1\big(S_1(0)\big) \tag{1}$$

$$\underbrace{+ \int_{t_1}^{t_2} e^{-\delta t} \left[\, B_2(R_2) - C_2^L(L_2) - C_2^R(R_2) \,\right] \, dt - F_2\big(S_2(t_1)\big)e^{-\delta t_1} - D_1\big(S_1(0) - S_1(t_1)\big)e^{-\delta t_1}}_{J_2}$$

where $C_i^L(L_i)$ and $C_i^R(R_i)$ are the costs of landfilling and recycling, respectively; both of them are strictly increasing, strongly convex and twice continuously differentiable. Landfilling costs are assumed to include also the environmental costs when old landfill is still in use. The benefits of recycling, $B_i(R_i)$, are expressed as a strictly increasing, strongly concave, twice continuously differentiable function of recycling. The fixed costs of opening landfill $S_i$ in the beginning of each period $i$ are captured by $F_i(S_i)$. The function $D_1(S_1(0) - S_1(t_1))$ represents the potential damage that an old landfill, with the total amount of waste $W_1(t_1) = S_1(0) - S_1(t_1)$ when closed at $t = t_1$, may cause. It may happen that no hazardous damage occurs, in which case $D_1(W_1(t_1))$ stands only for the environmental monitoring costs of the old landfill. These deterministic shut-down costs include both landscaping costs and the harm or inconvenience associated with the old landfill no longer in use.[7] Both $F(\cdot)$ and the damage cost function $D(\cdot)$ are linear with respect to their arguments. Linearity is a simplification, but given the data available, it is a relatively close approximation.

Functional (1) is maximized subject to the constraints

$$\begin{aligned}
\dot{S}_i &= -L_i, \quad i = 1,2 && (2)\\
\dot{S}_i &= 0, \quad t \geq t_i, \quad i = 1,2 && (3)\\
S_1(0) &= S_1^0, \qquad S_1(t_1) \geq 0 && (4)\\
S_2(t_1) &= \text{free}, \quad S_2(t_2) \geq 0 && (5)\\
G_i^* &= L_i + R_i, \quad i = 1,2 && (6)
\end{aligned}$$

where equations (2) and (3) are equations of motion for landfill spaces. In equations

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[7] Stricter environmental monitoring costs of new landfills which were neglected on the part of the old landfill are already taken into account in the fixed costs of the new landfill, $F_2$. Notationally $F_2$ and $D_2$ could be kept separate, but since this does not change the necessary conditions, and only adds complexity, the landscaping costs of the new landfill are included in the costs of building it.

(4) and (5) endpoint conditions say that when the landfill is closed at the end of the period, either the landfill is full or there may be some space available, but there cannot be more waste than there was space for in the beginning. The exogenous amount of waste generated, $G_i^*$, will be allocated to the landfill, $L_i$, or recycled, $R_i$, as equation (6) states.

We solve the problem as a two-stage optimal control problem.[8] The current value Hamiltonians for the problem are

$$\begin{aligned}
\mathcal{H}_1 &= B_1(G_1^* - L_1) - C_1^L(L_1) - C_1^R(G_1^* - L_1) + \lambda_1(-L_1), \quad t \in [0, t_1] && (7)\\
\mathcal{H}_2 &= B_2(G_2^* - L_2) - C_2^L(L_2) - C_2^R(G_2^* - L_2) + \lambda_2(-L_2), \quad t \in [t_1, t_2] && (8)
\end{aligned}$$

where equation (6) was used and $t_1$ is the switching time when landfill $S_1$ is closed and the new one, $S_2$, is opened.[9] The shadow price of the space stock, $\lambda_i$, reflects the scarcity or social value of the space available. Given constraints (2) - (6) and applying Pontryagin's Maximum Principle, the necessary conditions for this maximization problem are[10]

$$\begin{aligned}
\partial\mathcal{H}_i/\partial L_i &= -B_{R_i} - C_{L_i} + C_{R_i} - \lambda_i = 0, \quad i = 1, 2 && (9)\\
\dot{\lambda}_i &= \delta\lambda_i, \quad i = 1, 2 && (10)\\
\lambda_2(t_1) &= \frac{\partial F_2(S_2(t_1))}{\partial S_2(t_1)} && (11)\\
\lambda_1(t_1) &= \frac{\partial J_2^*}{\partial S_1(t_1)} = \underbrace{-\frac{\partial D_1(W_1(t_1))}{\partial S_1(t_1)}}_{+} && (12)\\
&- \mathcal{H}_2(t_1) + \underbrace{\delta F_2(S_2(t_1))}_{A>0} + \underbrace{\delta D_1(W_1(t_1))}_{B>0} + \mathcal{H}_1(t_1) = 0 && (13)
\end{aligned}$$

where $J_2^*$ is the maximized value of the objective functional of the second period.

Note that since 100% recycling is not possible, it follows that $L_i > 0$ and $\partial\mathcal{H}_i/\partial L_i = 0$ in equation (9) or we necessarily have an interior solution. As $S_2(t_1)$ and $t_1$ are determined

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[8] See Amit (1984), Tomiyama (1985) or Tomiyama and Rossana (1989).

[9] The Hamiltonians in (7) and (8) are written such that it is assumed $t_1 \in (0, t_2)$. In other words, if $t_1$ were 0 or $t_2$, we would only have either Hamiltonian $\mathcal{H}_1$ or $\mathcal{H}_2$ in the maximization problem or we would only use either the first or the second landfill, and no switch would be made. See, e.g., Amit (1984, p537).

[10] See, e.g., Bryson and Ho (1975, p87-89) and Seierstad and Sydsæter (1987, p185,Theorem 3.5). In particular, equation (13) is the optimal switching time condition corresponding to that presented by Bryson and Ho (1975, 2.8.20) or $\Omega = \left[ \frac{\partial J_2}{\partial t} + \frac{\partial J_2}{\partial S_1}\frac{\partial S_1}{\partial t} + B_1(R_1) - C_1^L(L_1) - C_1^R(R_1) \right]_{t=t_1}$.

optimally we need conditions (11) - (12).

The terms denoted by A and B on the left-hand side of equation (13) refer to the benefits of postponing the building of the second landfill in the beginning of period two: (A) fixed costs of preparing a new landfill will be delayed by the marginal increase in $t_1$ and (B) the shut-down costs of the old landfill will be further postponed. An intuitive interpretation is that the greater the future costs are, the more incentive there is to postpone them, or the more slowly the first landfill is used.

One should also note that the value of the costate variable $\lambda_1$ evaluated at the switch or at $t_1$ reflects the marginal value of additional space in the first landfill at the beginning of the second period as stated in equation (12). Hence, the space not used for waste disposal is the gain of not contributing to waste accumulation and the associated costs of the risk that hazardous damage will occur in the second period.

Conditions (11) and (12) for the costate variables capture the two types of tradeoffs to be considered in planning: 1) the relative costs of setting up and closing down two different, successive landfills, and 2) the relative damages caused by the same landfill in successive time periods, or today's versus tomorrow's environmental costs, i.e., prolonging the use of an old landfill is likely to increase its future environmental risks. To see more clearly these tradeoffs, we rewrite the Hamiltonians in (13) using (7), (8), (11) and (12)

$$\begin{aligned}&\left[B_1(G_1^* - L_1) - C_1^L(L_1) - C_1^R(G_1^* - L_1)\right]\\ &\qquad - L_1\left(-\frac{\partial D_1(W_1(t_1))}{\partial S_1(t_1)}\right) + A + B\\ &= \left[B_2(G_2^* - L_2) - C_2^L(L_2) - C_2^R(G_2^* - L_2)\right]\\ &\qquad - L_2\left(\frac{\partial F_2(S_2(t_1))}{\partial S_2(t_1)}\right) \qquad (14)\end{aligned}$$

where A and B refer to gains in postponing the fixed costs ($F_2$ and $D_1$). Consequently, when these kinds of tradeoffs are present, myopic behavior may result in intertemporally nonoptimal solutions.

To give an idea of what these tradeoffs would mean in practice, consider the consequences of the new environmental directives prepared by the European Union (EU). The new directives set stricter requirements on controlling environmental impacts of old landfills and preparing new landfill sites; both measures increase the set-up and shut-down costs of landfills. The expected stricter norms have resulted in closures of several landfills, because municipalities wanted to avoid the expected increased future costs caused by the new requirements. By closing landfills before the new norms were in effect, municipalities aimed to achieve short-term savings in the costs of monitoring old landfills and building new ones. Now, however, they may face a higher risk of potential damage resulting from their abandoning old landfills carelessly. At a more abstract level, the savings in $F_2(\cdot)$ and $D_1(\cdot)$ were realized through a neglect of social costs.

From (10), (11) and (12), it is seen that $\lambda_i(t)$ is non-negative and steadily increasing over the planning horizon. Accordingly, solving $\lambda_i = C_{R_i} - B_{R_i} - C_{L_i}$ from equation (9), also the net marginal cost of recycling can steadily increase relative to the marginal cost of landfilling, because the scarcity of landfill space makes $\lambda_i(t)$ increase over time. Obviously, recycling will be favored vis-a-vis landfill use over time.

Taking the time derivative of $\lambda_i = C_{R_i} - B_{R_i} - C_{L_i}$ and then replacing $\lambda_i$ and $\dot{\lambda}_i$ in (10), it follows that[11]

$$\dot{L}_i = \delta \frac{\overbrace{(C_{R_i} - B_{R_i} - C_{L_i})}^{+}}{\underbrace{(B_{R_iR_i} - C_{R_iR_i} - C_{L_iL_i})}_{-}} \tag{15}$$

The interpretation of the above equation is straightforward. Due to the strong curvature properties of the cost and benefit functions, the sign of the numerator is positive, since $\lambda_i = C_{R_i} - B_{R_i} - C_{L_i}$ is nonnegative. Thus, optimality necessitates that the differences in the net marginal costs result in a change in the relative use of the alternative technologies. Landfilling becomes a less attractive alternative than recycling over time due to the scarcity of landfill space. Municipal waste management authorities can attain the optimal disposal paths by choosing the level of landfilling such that the equality in (15) holds.

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[11] Here we assume that the amount of waste generated is constant. If $\dot{G} \neq 0$, then on the right-hand side there will be an extra term $\frac{(B_{R_iR_i} - C_{R_iR_i})}{(B_{R_iR_i} - C_{R_iR_i} - C_{L_iL_i})}\dot{G}$. The multiplier of $\dot{G}$ is positive and less than 1.

## 3 Simulation

Now that the control problem of the social planner has been investigated, a simulation of an optimal waste management plan using data from the Helsinki region in Finland is undertaken. The planning horizon chosen is 20 years, starting from 1995. It is assumed that during the next couple of decades no major changes will occur in recycling technology or costs. It is also assumed that the composition of municipal solid waste will remain the same during the planning period. These assumptions seem plausible given that in the recent past there have been no major changes in waste disposal other than in the amounts of waste generated. The waste volumes generated have followed changing economic conditions, which directly affect consumption.[12]

### 3.1 Data

All the data used in the simulation are summarized in Table 1.

The space available in the current landfill is estimated to be roughly 4 million tons. The costs of building a new landfill that meets the environmental standards of the European Union are estimated to be FIM 36.65 million[13] for a landfill with a total capacity of 2.27 million tons. Assuming that these costs are linear with respect to the capacity of the landfill, an estimate for building costs of FIM 16 per ton of waste is obtained.

The model also takes into account the shut-down costs of the first landfill. To begin with, it considers only the deterministic, or known, costs, i.e., the costs that result from landscaping and environmental monitoring of the old landfill. Later, when doing the sensitivity analysis, it will account for potential hazardous damage occuring in the old landfill by including the expected costs of cleaning up the landfill. The closing costs are reflected by the shadow cost of the current landfill space. Given that the cost estimate is a total of FIM 8 million, the shadow cost of the space in the first landfill at switching time is approximately FIM 2 per ton of waste.[14]

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[12] During the steady economic growth in the 1980s, waste streams increased by 5 to 6 % annually. In the recent economic recession the growth rates have turned to a downward trend in the amount of municipal wastes generated.

[13] To convert Finnish marks to US dollars, use 1 FIM = 1/5 US$.

[14] All these cost estimates are from a study prepared by Suomen kaupunkiliitto (1992) (The Association of Finnish Local Authorities) to provide Finnish municipalities with estimates of expected costs of using landfills which meet the new, tighter environmental standards.

The cost estimates of operating landfills and recycling are based on the experience of current practice, i.e., processing, disposal and collection costs and on future estimates calculated by the Helsinki Metropolitan Area Council (YTV (1993)).[15] The recyclable items to be considered in the simulation are paper, cardboard, organic waste, glass, metal and plastic.

The results of the recent contingent valuation (CV) study are used to include the demand effects in the simulation. In the study, households were asked which disposal method, incineration or large-scale recycling, they would prefer in order to alleviate the problems of landfilling in the Helsinki region. They also indicated whether they were willing to pay more for the preferred disposal option. Recycling proved to be a far more popular option than incineration. Approximately 70 % of the survey sample supported the recycling alternative provided it did not involve any extra costs to the households or the price of the recycling disposal services ($p^R$) was 0. Also, given that a maximum 70 % of municipal waste is recyclable, about half of the annual waste stream could be recycled. Hence, households' demand for recycling services ($R_d$) is at maximum at no extra cost (or $p^R = 0$, $R_d = R_d^{max} = 300{,}000$). The CV results indicate that if large-scale recycling cost more than any other option (or incineration in the CV study), the demand for recycling would decrease with extra cost. To determine a choke price ($p^c$) on the demand curve, the demand for recycling disposal services is assumed to be zero at FIM (Finnish marks) 120 extra annual cost (or $p^R = p^c = 120$, $R_d = 0$). This is the mean maximum willingness to pay extra for recycling computed from the CV survey responses. The approximation of consumer surplus may be an under(over)estimate, since in the sample there were people who were willing to pay more (less) than the mean value. However, the mean is a widely used welfare measure, and here its use is justified to account for the *non-market benefits* that consumers associated with recycling, i.e., benefits other than the raw material value of wastes. A common reason to prefer recycling was the air pollution that could be avoided if municipal waste was not incinerated. Also the environmental friendliness of recycling was frequently mentioned in the survey responses.

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[15] The Helsinki Metropolitan Area Council is responsible, among other things, for waste disposal in the region. As a waste management authority, the Council has produced, with the help of engineering consultants, alternative plans for solving the waste management problems. These plans are summarized in the report "A proposed waste management plan for the Helsinki region". To compare the Council's estimates with US cost estimates see, e.g., Morris (1991).

The simulation model allows us to reduce the amount of waste generated. An annual reduction of two percent and a total reduction of up to ten percent in the initial amount is possible. Finally, the last parameter to be defined is the discount rate, which is here set at 5 percent.

### 3.2 Results

The model was calibrated and solved using GAMS (Brooke et al. (1988)) with the initial values discussed above. The optimal levels of recycling and landfilling are illustrated in Figures 1 and 2. The results show that all paper, cardboard and metal, but none of the glass or plastic, should be recycled. As expected from the theoretical model, the landfill use rate declines over the planning horizon. This is made possible by steadily increasing the recycling rate for organic waste. There is a particular upward jump in the recycling rate at the time a new landfill is opened. This reflects the higher costs of new landfills, which are built according to more stringent safety standards. It should also be noted that an optimal plan would initially decrease the amount of waste generated as much as possible. Of course, this is a trivial result in the sense that we assumed waste reduction to be costless, but the model could be adjusted to take into account potential reduction costs, such as information campaigns to consumers and the packaging industry. The problem is, however, that there is basically no information on what it would cost to achieve higher levels of source reduction.

The results of the simulation are summarized in Table 2 and indicate that recycling significantly prolongs the lifespan of landfills. To test the robustness of the results, their sensitivity to the demand for recycling disposal services and to the landfilling costs were explored.[16] First, the model was re-run with the consumer surplus associated with recycling lowered to two-thirds of its initial value in the base model. With this value, the total amount of recycling would decrease: all paper, cardboard and metal would still be recycled, but less organic waste would be recovered. Organic waste recycling would first

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[16] Sensitivity to the closing costs of the old landfill was also studied. We assumed that there is a 10-percent risk that hazardous damage will occur in the old landfill and that this results in a tenfold increase in the closing or cleanup costs. As expected, recycling became an even more favorable alternative, but despite the relatively significant risk, the results were virtually identical with the base case. However, the relatively small increase in recycling supports the theoretical model, which predicts that the landfilling option will become less attractive.

drop to one-third of the amount in the base model but would then increase gradually and, in the end, be about 70 % of the initial baseline amounts. Second, the sensitivity of the model solution to changes in the landfilling costs was addressed. When the landfilling costs are raised by one-third, complete recycling of organic waste is optimal. Also, glass recycling would become economically viable under this cost scenario, and by 1999 all of the recyclable glass should be recovered.

The optimal recycling rate[17] lies in the range of 31 to 51 % under different scenarios (see Figure 3), whereas the weighted mean for the recycling rate over time is about 42 percent.

## 4 Concluding Remarks

This paper examined how to allocate available and future landfill capacity over time in a socially optimal way when recycling is considered as an alternative waste disposal option. It has been claimed (see, e.g., Goddard (1995)) that in waste management problems are still viewed as technological deficiencies requiring engineering "end-of-the-pipe" solutions. This paper, instead, attempts to plan waste disposal in an economically efficient way in the sense that it is modeled as a decision problem involving choices over time under scarcity of resources. A dynamic waste management optimization problem was solved taking into account both the economic and environmental benefits and costs associated with each disposal option.

It was important to include the demand effect measured by households' willingness to pay for recycling in the model, since the proper working of a large-scale recycling program depends heavily on households' sorting efforts. To make the analysis more realistic, demand for secondary raw material should be taken into account. The problem is that as long as more specific data are not available, it can only be assumed that "everything goes" at a given price. However, the model can easily be modified if better data on demand should become available.

The analysis shows that when the social (environmental) costs of landfilling are taken into account, it becomes a more costly disposal option than others. The results of the study suggest that mandates for achieving 50 % recycling in municipalities are not too

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[17] The ratio of the total amount of waste recycled to the total amount waste generated.

far-fetched and are both economically and environmentally justified.

Figure 1: Optimal Levels of Recycling and Landfilling (tons)

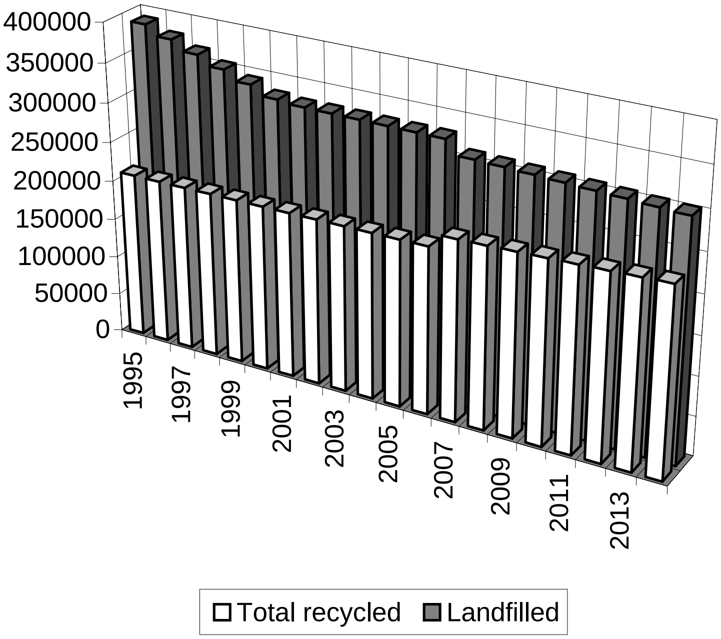

Figure 2: Optimal Recycling Levels by Items (Base Model, tons)

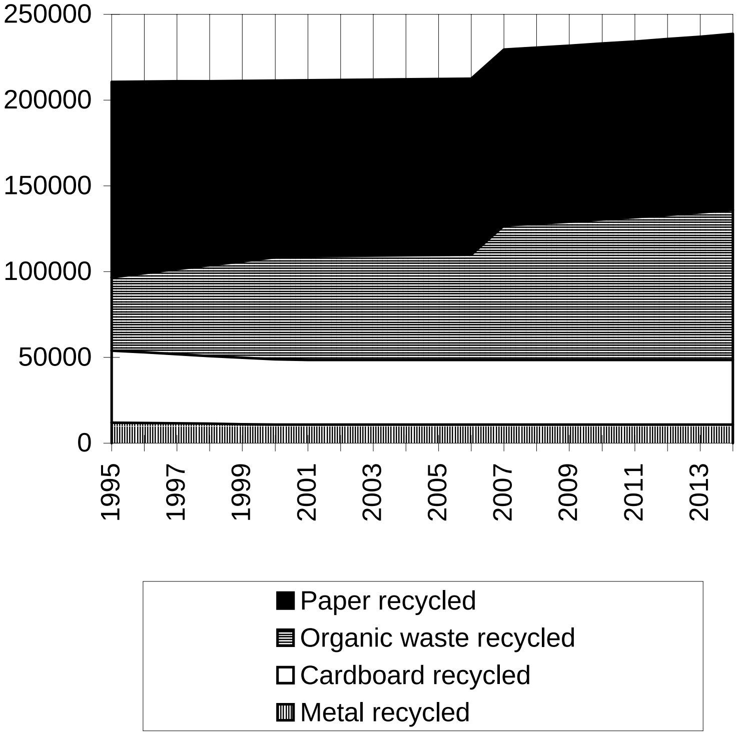

Figure 3: Recycling Rates under Different Scenarios (%)

Table 1: Data

| **Costs** | | **FIM/ton** |
|---|---|---|
| *Landfilling* | | |
| The shadow cost of | | |
| · building new capacity | $\lambda_2(t_1)$ | 16 |
| · shutting down old landfill | $\lambda_1(t_1)$ | 2 |
| Disposal + collection | $C_i^L(L_i)$ | 550 |
| *Recycling* | | |
| Net cost[a] | | |
| · paper (19) | $C_i^R(R_i)$ | 0 |
| · metal (2) | | 190 |
| · cardboard (7) | | 400 |
| · organic waste (21) | | 450 |
| · glass (2) | | 580 |
| · plastic (3) | | 2100 |

**Non-market benefits**

*Demand for recycling (linear)*

$p^R = 0 \quad \Rightarrow R^d = R_d^{max} = 300,000$

$p^R = p^c = 120 \quad \Rightarrow R_d = 0$

**Other parameters**

| | | |
|---|---|---|
| *Planning horizon* | $t_0 - t_2$ | *1995-2014* |
| *Discount rate* | $\delta$ | *0.05* |
| *Capacity of current landfill* | $S_1(t_0)$ | *4,000,000 tons* |
| *Initial annual waste stream* | $G_i^*$ | *600,000 tons* |

[a] Collection costs - sales revenue. Also the proportion of municipal waste, or the upper bound on the recyclability of the item, are given in parentheses. Source: YTV (1993).

Table 2: Summary of the Results of the Base Model and Two Sensitivity Analyses

*A total of 11 million tons of household waste handled during 20 years:*

| Scenario | Old landfill used, $t_1$ | New landfill capacity needed, $S_2(t_1)$ | Average recycling rate | Total costs, FIM |
|---|---|---|---|---|
| Base model | 12 years | 2,450,000 tons | 40.1 % | 2.54 billion[a] |
| Sens.analysis1[b] | 11 years | 3,000,000 tons | 35.4 % | 2.60 billion |
| Sens.analysis2[c] | 15 years | 1,323,000 tons | 50.9 % | 3.22 billion |

[a] By comparison, if no recycling took place, the total costs would be approximately the same, and the same landfill space would last for only 12 years instead of 20.

[b] Sens.analysis1: Consumer surplus lowered by one-third compared to the base model.

[c] Sens.analysis2: Landfilling costs raised by one-third compared to the base model.

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