Municipal Recycling: A System Dynamics Model

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Problem Definition

The available empirical data suggests that recycling – the percentage of municipal solid waste (MSW) recycled – grows exponentially at first, and then starts to level off. This is a classic S-shaped growth and saturation behavior. In addition, both population and per-capita waste-generation are growing, and the total waste generation (expressed as population x per-capita waste) appears to be growing exponentially. Thus, we may be entering a period where MSW continues to increase without a corresponding increase in the percentage of waste recycled. The total amount of MSW that is landfilled every year is likely to grow fast in the "business-as-usual" scenario that is currently unfolding.

My first task is to simply model the above behavior precisely, keeping the size and complexity of the model as small as possible. Following this, I will explore several mechanisms that can potentially increase the percentage of waste recycled and reduce the growth in landfilled waste. The purpose of the modeling is to gain insight into what factors might influence the recycling behavior of a population and how this behavior could be modified, rather than make specific predictions about what might happen in the future.

The time horizon that I have chosen is 1989 to 2000 for historical behavior, based on the availability of high-quality annual data. The starting year for all the simulations will be 1989. For the baseline case, the simulation results should match the historical behavior until 2000, and then for subsequent years the results could be seen as forecasting future behavior. For simulation of other scenarios, including policy options, the results will reflect both backcasting and forecasting based on the specific feedbacks introduced in the models.

The key variables of interest are: annual MSW tonnage (AnnualMunicipalSolidWaste), percentage of MSW recycled (PercentRecycled), and annual tonnage of landfilled solid waste (AnnualLandfilledWaste).

The model includes the following endogenous elements: a simple population with a net growth rate, growing per-capita waste generation, recycling policies and technologies, and recycling behavior of the population.

The following will be exogenous: The state of the economy (which may influence per-capita consumption and waste), recycled content of manufactured products, prices of virgin materials vs. recycled materials, etc.

The levels of aggregation will be as follows: All recyclable materials (such as paper, plastic and glass) will be lumped together, in order to keep the model fairly small. Population, and not households, will be the source of waste generation, in order to match the available data properly. The population will be divided into recyclers and non-recyclers, ignoring the possibility of partial recyclers who may recycle to varying degrees. All recyclers will be assumed to recycle to the fullest possible extent. These decisions about aggregation represent simplifications that are hopefully reasonable considering the purpose of the model.

Reference Behavior Patterns

There are generally two main sources of national data on solid waste management in the U.S. One is the periodic survey conducted for the Environmental Protection Agency and published under the title "Municipal Solid Waste in the US: Facts and Figures"[1]. The other is Biocycle magazine's "State of Garbage in America" survey[2]. I decided to use the Biocycle survey because it provides consistent annual data starting from 1989, when recycling was in its infancy. In contrast, the EPA does not provide this type of annual data.

I chose to use the Biocycle data from 1989 through 2000, because their methodology changed after 2000 and the subsequent data was no longer compatible with the 1989-2000 data. Thus, the reference behavior pattern (RBP) is as follows for the baseline (business-as-usual) case in this exercise:

Year	AnnualMunicipalSolidWaste (tons)	PercentRecycled
1989	269000000	8
1990	293613000	11.5
1991	280675000	14
1992	291742000	17
1993	306866000	19
1994	322879000	23
1995	326709000	27
1996	327460000	28
1997	340466000	30
1998	374631000	31.5
1999	382594000	33
2000	409029000	32

The above data represents an S-shaped growth and saturation in PercentRecycled, and an exponential (albeit slow) growth in AnnualMunicipalSolidWaste. The data applies to the U.S. population as a whole, and does not track the behavior of households. These curve shapes will be highlighted later with graphs while comparing it with simulation results.

In addition, empirical data from both Biocycle and EPA show that maximum landfill volume is not a real constraint, because many states have plenty of landfill space remaining. Waste can also be shipped now to other states that can have excess landfill capacity. Thus, landfill volume doesn't influence the cost of municipal garbage service as much the cost of actually handling and processing the garbage.

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[1] EPA's 2001 report (http://www.epa.gov/epaoswer/non-hw/muncpl/msw99.htm).

[2] S.C. Kaufman, N. Goldstein, K. Millrath, N.J. Temelis, "The State of Garbage in America", Biocycle Magazine, January 2004, pp. 31-41 (http://www.jgpress.com/archives/_free/000089.html).

Dynamic Hypothesis

After reviewing the baseline RBP, I formed the following hypotheses about the reasons behind the growth characteristics in the municipal solid waste data and what might be the best leverage points to tackle the problem.

- The exponential growth in AnnualMunicipalSolidWaste is clearly due to positive feedback. Both population and per-capita waste-generation are growing exponentially, and the product of the two results in an exponentially growing AnnualMunicipalSolidWaste.
- PercentRecycled grows in the early years of recycling due to positive feedback and then starts to level off due to multiple reasons (all of which include negative feedback dominating in later years):
    - Difficulties in recycling more, such as:
        - Too much trouble to sort or set aside more recyclable garbage
        - Too much trouble to clean and prepare more recyclables – either reduces quantity picked up or results in some portion of "recycled" materials actually landfilled after pick up due to contamination.
        - Many garbage companies pick up only certain types of recyclables, most likely due to some technological limitations – for example, in Washington County, the only plastics that are accepted are those in a bottle shape, even though other plastic products (such as yogurt containers) are made with the same type of plastic.
        - Some products/packages are made with multiple materials (such as combinations of plastic and metal, or plastic and glass) and are not suitable for recycling.
    - Cost of landfilled garbage not high enough to force more recycling
        - My sense from reviewing a lot of data and analysis is that landfill cost is not a strong driver at the moment. Also, considering what I have observed over the years, recycling is still a voluntary non-economic activity to a large extent.
    - Market for recycled materials is limited
        - If cost of landfilling were increased significantly through environmental taxes (regardless of maximum available space), then recycling would be much more attractive. Customers would find it cheaper to recycle than throw away.
        - Alternately, if cost of virgin raw materials were increased significantly through environmental taxes, then again recycling would be much more attractive economically. Garbage companies might even pay their customers to recycle! But this will likely require a model much more extensive than what I have planned for this exercise, so I will just experiment with a landfill tax.
- Most effective policy levers to increase recycling are likely to be:
    - Manufacturing end:
        - Require products and packages to be easier to disassemble and recycle, through improved manufacturing technologies.
    - Consumer end:
        - Increase cost of landfilling via taxes, which would be passed on to consumers and encourage more recycling and less landfilling.

        - Less stringent cleaning and sorting requirements, through improved recycling technologies.
    - Market end (not modeled in this exercise):
        - Increase cost of virgin raw materials (paper pulp, petrochemicals for plastics, energy, metal ores from mining, etc.), which would make recycled materials more attractive. Recycling would also use less energy than extracting and processing virgin raw materials.
- It is also likely that action by environmentally-conscious citizens (including those characterized as "Recyclers" in this exercise) could bring change that governmental action alone can't. In particular, there is potential for powerful reinforcing (positive) feedback loops when ordinary citizens become agents of change at the grassroots level. For example, this could include actively converting non-recyclers into recyclers, pressuring manufacturers to make recycling-friendly products and packaging, and work toward a society that creates less garbage in the first place.

Verification/Validation Checklist

I used the following checklist for debugging, verification and validation for all cases and models in this exercise:

- Vensim "Check Model"
- Vensim "Check Units"
- Eliminate dt issues and artifactual delays – try successively smaller dt's and also Runge-Kutta integration
- Check for any unexpected behavior, such as negative stocks
- Test by decoupling sub-models and neutralizing loops, as needed (partially avoided by incrementally adding sub-models and feedback loops to the model – Cases 1 through 7 – and testing at every stage)
- Walk through model logic, fully exercise, make sure model responds similar to mental model or hypothesis
- Compare results to RBP, fine-tune as needed
    - RBP exists for the baseline case (Case 1) and will be compared with simulation results
    - For other cases, RBP does <u>not</u> exist, so there will be no explicit comparison with an external reference. In general, for Cases 2-7, the percentage of recycled waste is expected to increase in varying degrees and annual landfilled waste is expected to decrease. However, the relative strengths the policy or social actions modeled in these cases are not known.
- Check all parameters for validity – look at Vensim table and graph outputs
- Sensitivity analysis
    - Select a set of critical parameters to test
    - Vary one at a time by +/-20% and document change in final results – create table of results
    - Double check parameters that the model is highly sensitive to

Model Development, Verification and Validation

This section describes the models that I built to replicate the RBP first and then explore various policy and social mechanisms that might increase recycling and reduce landfilled waste. Each case below builds incrementally on the previous case, making verification and validation much easier. Each case also includes selected highlights of the verification and validation done for that case.

Case 1: Baseline recycling model with population growth

I decided to include a simple population model as a driver in the baseline model in order to match the RBP (the RBP reflects growth in population and consumption). The purpose of this model is to approximately match the historical data from 1989 to 2000, and then provide some insight into how landfilled waste might grow in the future.

Figure 1 below shows the Vensim model for this case and Attachment 1 at the end includes the model equations.

After calibration of the parameters, Figure 2 shows the basic results in terms of the key variables. As expected, AnnualMunicipalSolidWaste grows exponentially (but slowly), PercentRecycled exhibits an S-shaped growth, and AnnualLandfilledWaste rises sharply after PercentRecycled saturates. Time starts in the year 1989 (X = 0). The reference data ends in year 2000 (X = 11). The time unit is years and the simulation time step is one year.

The key structure and parameters of the baseline (Case 1) model are as follows:

- Population is modeled with a fractional net growth rate of 0.01/year. I actually estimated this parameter approximately by looking at actual U.S. census data[3].
- Annual per-capita waste generation is modeled with a fractional increase rate of 0.028/year. This parameter was obtained by calibration in order to make AnnualMunicipalSolidWaste match its RBP.
- The product of the above two exponentially growing stocks yields the exponentially growing AnnualMunicipalSolidWaste.
- A certain percentage of the population (PercentRecyclers) is assumed to be committed to recycling at the beginning in year 1989. This initial value for PercentRecyclers works out to be 15 (%), so PercentNonRecyclers starts at 85 (%). The initial values were obtained as part of the calibration step to match the RBP for PercentRecycled.
- As PercentNonRecyclers decreases at some varying rate, PercentRecyclers increases by the same rate. This part of the model is very similar to epidemic models in that the "infection rate" (rate at which non-recyclers become recyclers), depends on the number (or percentage in my model) of non-recyclers and the recycling fraction of the population. This rate can be reduced by other limitations, such as ease of recycling, insufficient cost of landfilling and highly resistant non-recyclers.
- PercentRecyclers exhibits a classic S-shaped growth, which leads to another (less ideal) S-shaped growth in PercentRecycled as seen in Figure 2.
- I have implicitly assumed that population growth will not change PercentRecyclers or PercentNonRecyclers. This implies that both parts of the population grow at the same rate. I thought this was a reasonable assumption -- when there are more recyclers, proportionately more babies are likely be born in recycling families and start out as recyclers, etc. (ignoring immigration for the moment, or assuming that new immigrants become recyclers/non-recyclers in the existing proportion).
- Using the above assumptions, I have separated the population growth from the recycler/non-recycler percentages, and brought the two parts of the model together only to calculate the actual amount of waste that is recycled.
- FractionRecyclable (amount of solid waste that is intrinsically recyclable) is 0.55 (55%), based on calibration as well as estimation from my own experience.
- EaseOfRecycling (how easy it is to recycle, how much cleaning/sorting required, etc.) is 0.5 (55%), based again on calibration and estimation from personal experience.
- PercentResistantNonRecycers is 40 (%) – meaning that 40% of the population will not recycle unless the cost of landfilling is very high.
- CostOfLandfilling is $2500/ton (somewhat on the high side) – but is designed not to affect the results of the baseline model.
- CostPainThreshold is $5000 – the landfilling cost per ton at which non-recyclers have a high incentive to switch.

[3] http://www.census.gov/main/www/cen2000.html ; http://www.census.gov/population/censusdata/table-2.pdf .

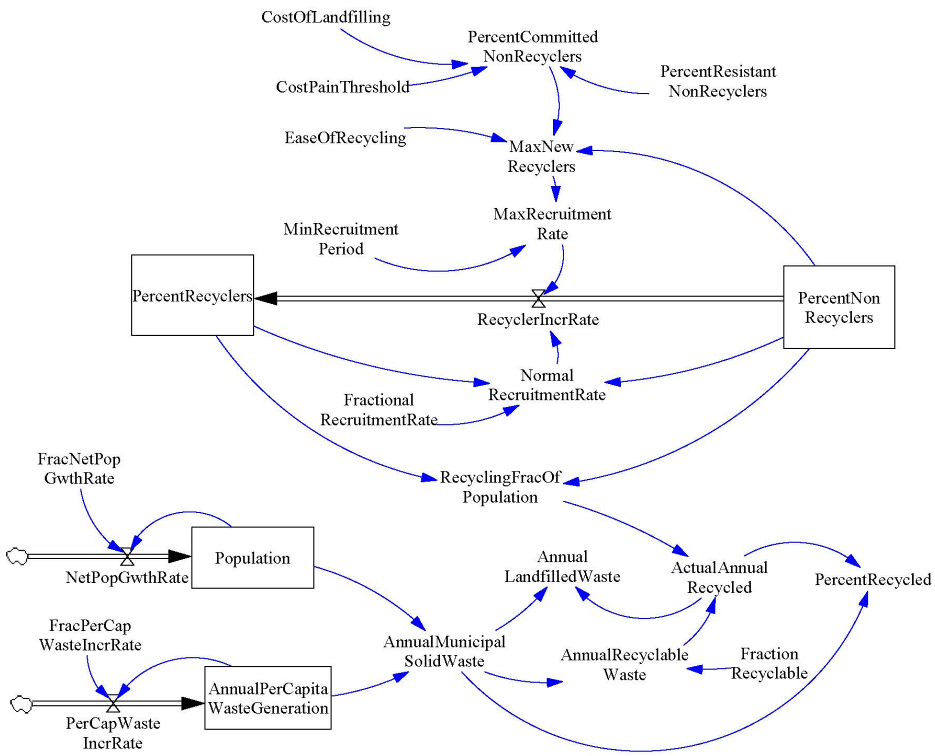


Figure 1: Case 1 (baseline) model for recycling with population growth

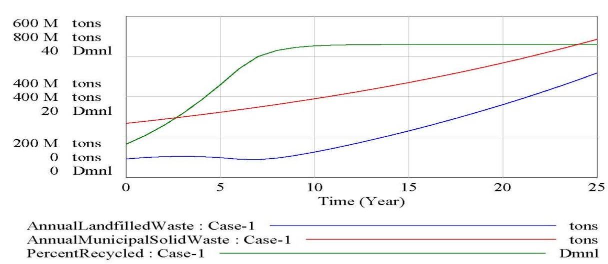
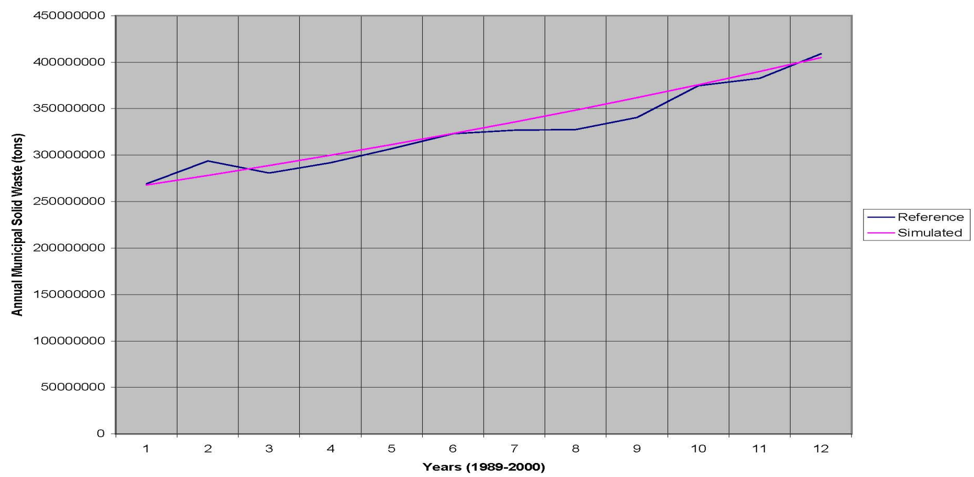


Figure 2: Case 1 results

Highlights of verification and validation

For Case 1, I did not find any significant difference in results with shorter dt values, as well as while re-running the simulation with Runge-Kutta integration. Since I was not able to import the RBP into Vensim's PLE version, I used Excel to graph the reference and simulated behavior as shown in the figures below (X-axis values in Excel graphs range from 1 to 12 for years 1989-2000). I believe that the results are sufficiently close to the RBP, with the difference that the smooth simulated results can't track the noise-like variations in the actual data.



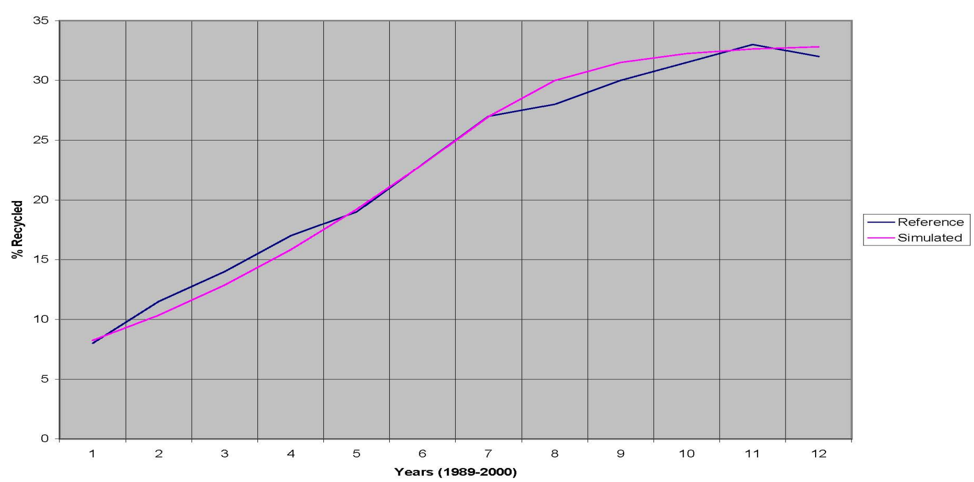


Figure 3: Case 1 results compared to RBP

The other part of verification and validation worth reporting in some detail is the <u>sensitivity analysis</u>. I varied each parameter by +20% and -20%, keeping other parameters at their base values, and measured the response by looking at the simulated PercentRecycled and AnnualLandfilledWaste for year 2000. The results for 5 key parameters and initial conditions are shown below.

Parameter or Initial Condition	Variation	PercentReycled in 2000	AnnualLandfilledWaste in 2000 (millions of tons)
(All nominal values)	-	32.81	272
PercentResistantNonRecyclers	+20%	28.51	289
	-20%	37.00	255
EaseOfRecycling	+20%	32.94	271.5
	-20%	32.53	273
FractionalRecruitementRate	+20%	32.90	271.7
	-20%	32.49	273
FractionRecyclable	+20%	39.37	245
	-20%	26.25	298.6
PercentRecyclers (initial condition)	+20%	32.89	271.7
	-20%	32.64	272.7

Clearly, the results are highly sensitive to PercentResistantNonRecyclers and FractionRecyclable, but show low sensitivity to the other parameters. These two parameters seem to be good candidates as leverage points for policy and social action, and will be used in such feedback loops in subsequent models.

<u>Case 2: Higher landfill cost (policy-based feedback)</u>

The cost of landfilling did not influence the results in Case 1. The first incremental change to the model is to vary CostOfLandfilling such that it increases (decreases) linearly as PercentRecycled decreases (increases). This requires an additional feedback link as shown in the model below. I also included an information delay, with an adjustment time of 2 years, to model a delayed policy response.

The results in Figure 5 show a significant increase in PercentRecycled when the cost of landfill depends directly on how much is recycled (rather than landfill capacity or other factors). As recycling saturates – now at about 42% -- due to balancing feedbacks, the cost of landfilling stabilizes at a rather high value (this is not so obvious in the graph).

<u>For Cases 2-7, I used the same verification/validation checklist as in Case 1, except that these additional cases are speculative experiments in policy and social action for which no real world RBP is available. So, I focused more on sensitivity analysis (see table below for a sampling), dt issues, and other aspects of verification/validation to make sure that these models are as correct as possible without benefit of external reference data. I</u>

made sure that the results are along the lines of what I expected and investigated anything that looked surprising.

Parameter or Initial Condition	Variation	PercentRecycled in 2000	AnnualLandfilledWaste in 2000 (millions of tons)
(All nominal values)	-	41.94	235
CostIncrement	+20%	43.1%	230
	-20%	40.3%	241.7
RecyclingPolicyAdjustmentTime	+20%	42	234.7
	-20%	41.86	235

The results are quite sensitive to CostIncrement (the incremental cost of landfilling each additional ton of waste), as expected.

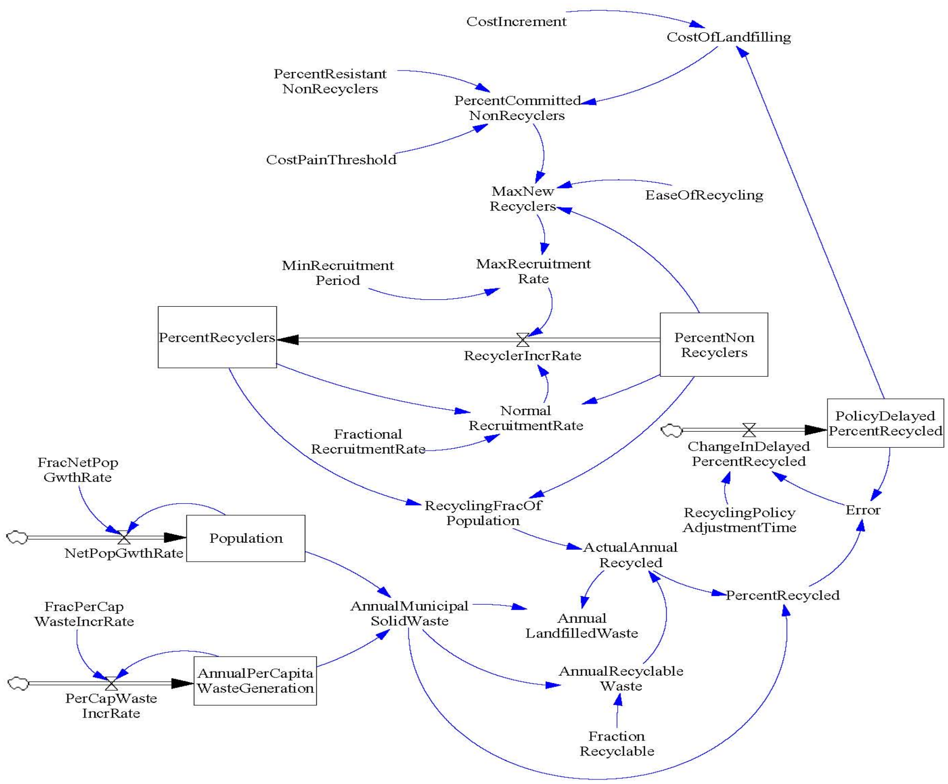


Figure 4: Case 2 model with variable landfill cost

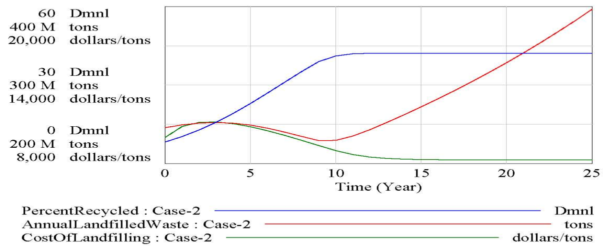


Figure 5: Case 2 results

Case 3: Easier recycling (policy-based feedback)

The next policy experiment is to force changes in recycling methods and technologies, to make it easier for people recycle more without spending a lot of time cleaning, sorting, etc. The model and results are shown in Figures 6 and 7 respectively. Feedback from policy response to PercentRecycled now drives changes in recycling technology. I have added an additional delay for changes in recycling technology, with an average time constant of 2 years. The results show that PercentRecycled does not increase appreciably even as EaseOfRecycling reaches its full value of 1, which is a surprise. The reason is that EaseOfRecycling helps when non-recyclers are willing to change, but it does not change PecentCommittedNonRecyclers in my model.

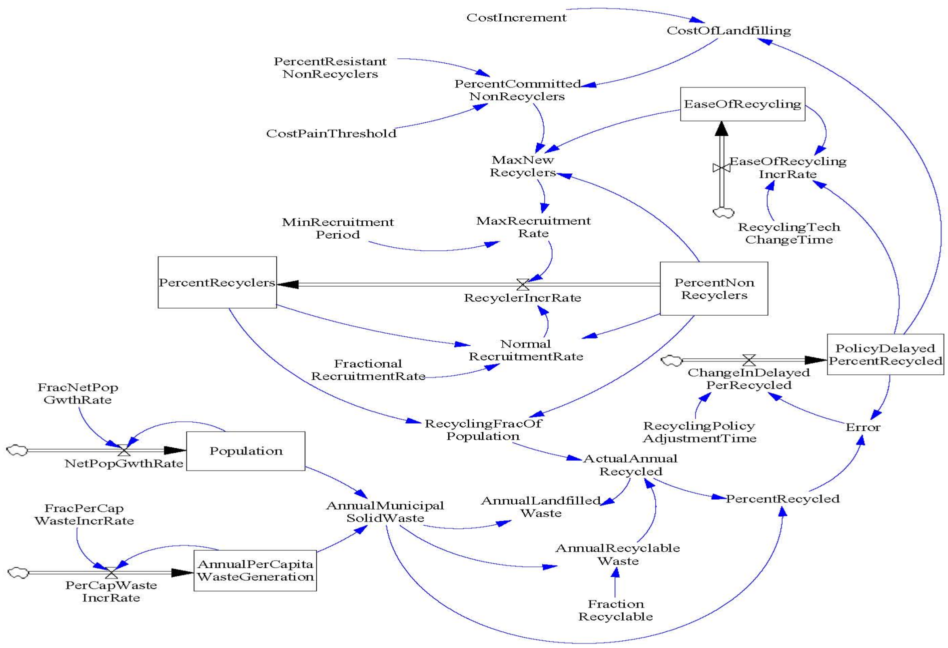


Figure 6: Case 3 model

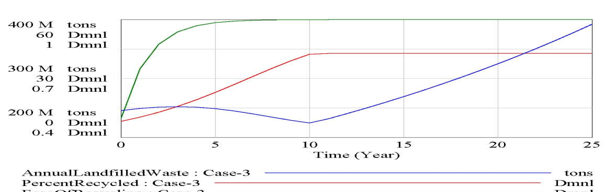


Figure 7: Case 3 results

Case 4: Improved manufacturing to help recycling (policy-based feedback)

The final policy-based feedback experiment is directed at increasing FractionRecyclable through better manufacturing technologies. Feedback from policy response to PercentRecycled now drives changes in manufacturing technology, with an average time constant of 5 years for any changes.

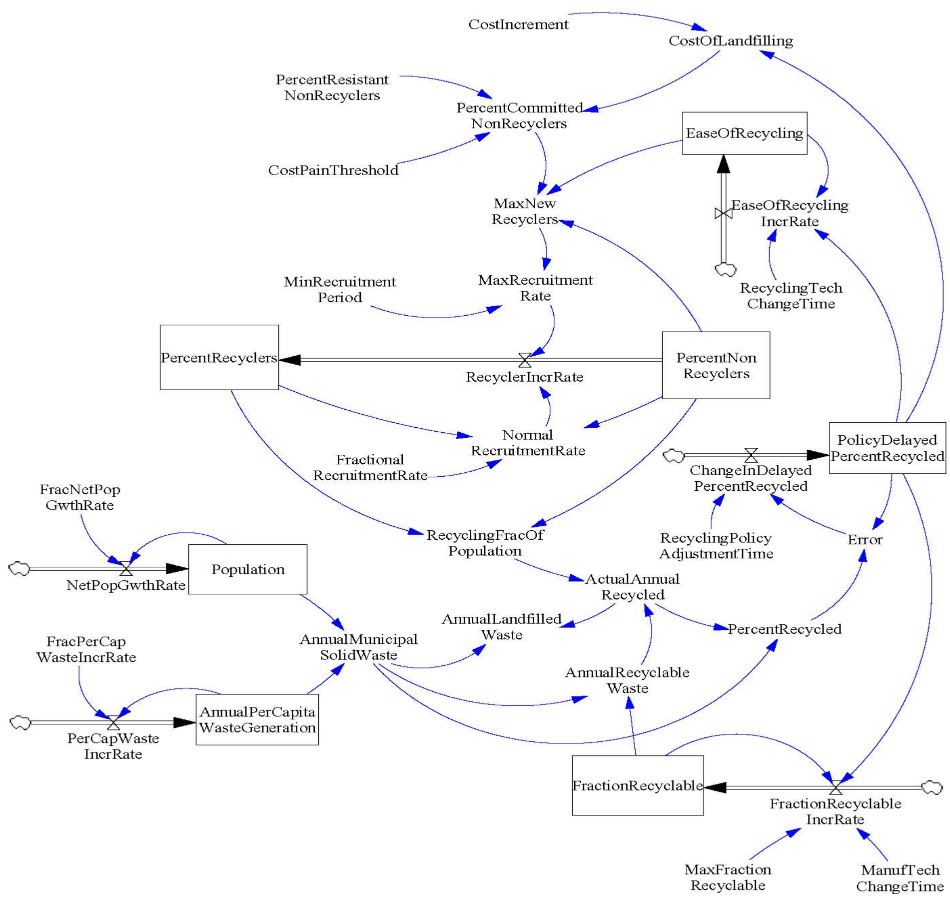


Figure 8: Case 4 model

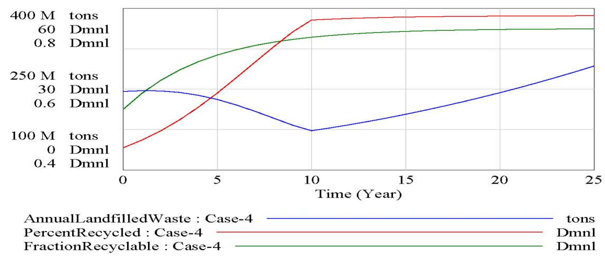


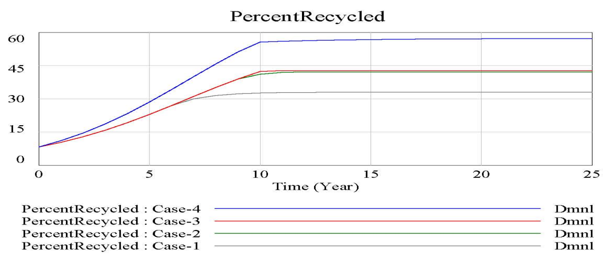
Figure 9: Case 4 results

Similar to increased landfill costs, improved manufacturing technology is another high-leverage point for policy action. As more products and packaging are designed and manufactured to be easily recyclable, it dramatically increases the percentage of waste that is actually recycled. I have assumed for now that up to 75% of waste can be potentially made recyclable with better technologies.

Figure 10 below compares the results from Cases 1-4 and shows how PercentRecycled jumps up when landfill costs and manufacturing technologies are driven through feedback loops from PercentRecycled. In all cases, PercentRecycled continues to exhibit an S-shaped curve and saturates at higher values as a result of various policy interventions. In each case, the saturation of PercentRecycled at less than 100% indicates some remaining limitation in the system.

The following table shows the high sensitivity of the results to the maximum fraction of waste that can be recycled:

Parameter or Initial Condition	Variation	PercentRecycled in 2000	AnnualLandfilledWaste in 2000 (millions of tons)
(All nominal values)	-	55.99%	178
MaxFractionRecyclable	+20%	60.4%	160
	-20%	51.17%	197.7



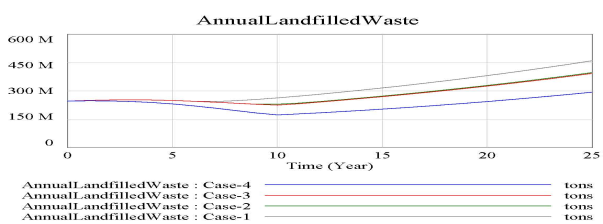


Figure 10: Comparison of cases 1-4

Case 5: Activist recyclers (social feedback)

This is the first of three speculative experiments on what could happen through social action, as opposed to public policy set by elected officials. Given the high sensitivity of the results to MaxFractionRecyclable, the following model and results show the potential effect of recyclers pushing manufacturers to produce more recycling-friendly products and packaging. Recyclers could do this by campaigning as well as demonstrating their intent through purchasing decisions. This would reduce the landfill costs paid by consumers and help the environment. The feedback added here is from PercentRecyclers to MaxFractionRecyclable. MaxFractionRecyclable increases linearly as PercentRecyclers increases. PercentRecycled jumps from about 56% (Case 4) to 65% in this case and AnnualLandfilledWaste drops from 178 million tons to 142.

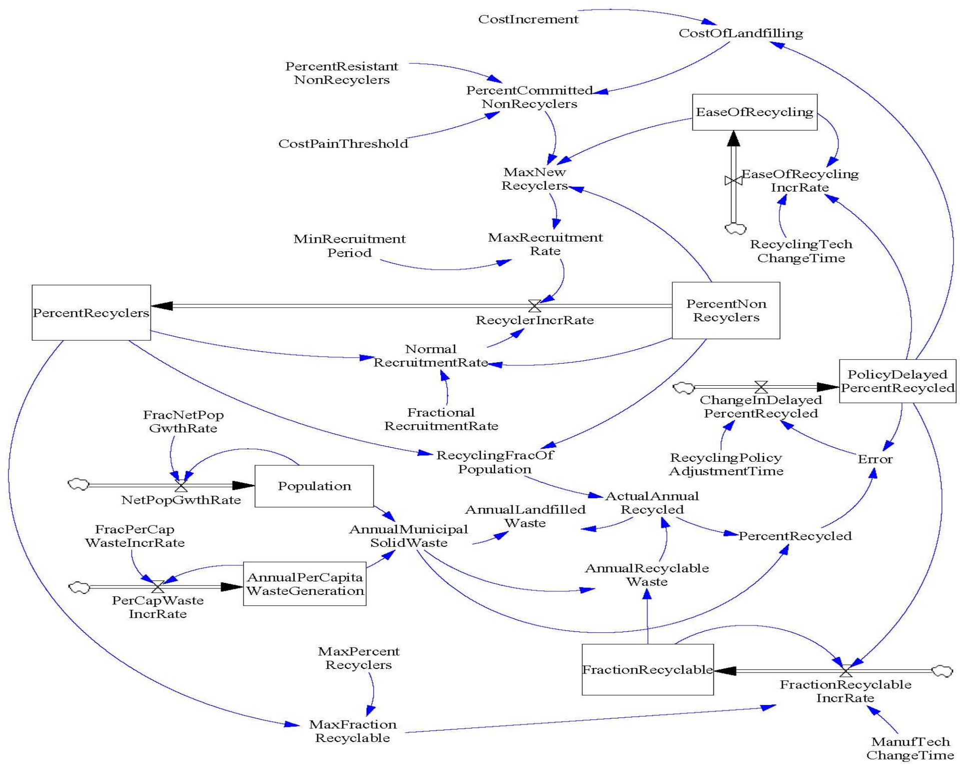


Figure 11: Case 5 model

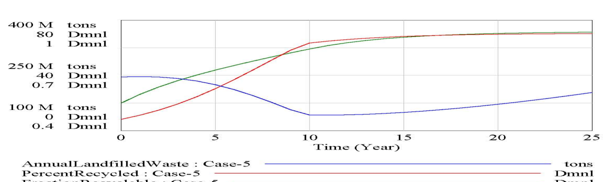


Figure 12: Case 5 results

Case 6: Evangelist recyclers (social feedback)

Recyclers could go a step further and try to influence non-recyclers through educational campaigns and personal contact. Here, an increase in PercentRecyclers decreases PercentResistantRecyclers through a "1/X" type of function. PercentRecycled jumps up again to 71% and AnnualLandfilledWaste drops to 117 million tons.

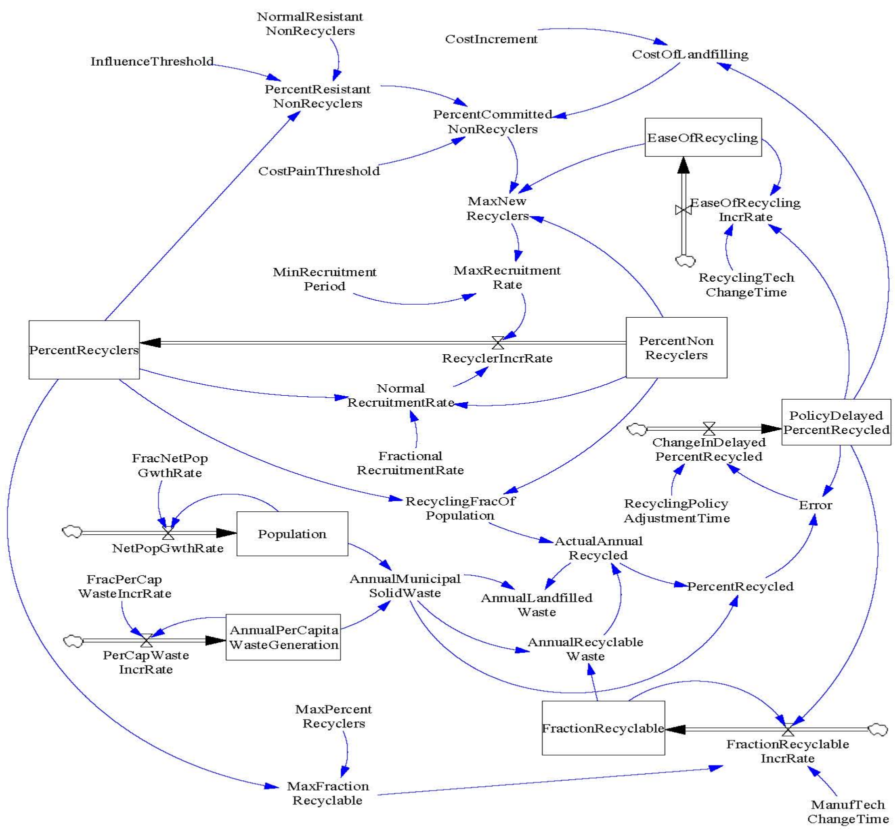


Figure 13: Case 6 model

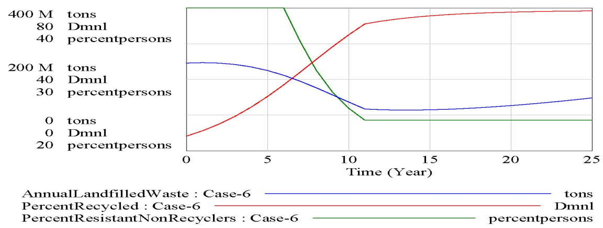


Figure 14: Case 6 results

Case 7: Waste reduction (social feedback)

The final experiment targets waste generation at its source rather than recycling per se. Here, recyclers campaign and work for reducing per-capita waste generation. As more people turn into recyclers, more effort goes into reducing waste in the first place. Again, the motivations for this would be reduced landfill costs and improved environmental quality. The model and results are shown below in Figures 15 and 16.

The additional feedback here is from PercentRecyclers to FracPerCapWasteIncrRate. As more people recycle and become aware of their environmental responsibility, the per-capita waste increase rate decreases. Once PercentRecyclers saturates, the per-capita waste generation starts to increase very slowly. As expected, this does not change PercentRecycled, but it does decrease AnnualLandfilledWaste from 117 million tons to 102 in year 2000.

The following sensitivity analysis shows that the results are not very sensitive to the main parameter controlling this feedback.

Parameter or Initial Condition	Variation	PercentRecycled in 2000	AnnualLandfilledWaste in 2000 (millions of tons)
(All nominal values)	-	71%	102
BaseFracPerCapWasteIncrRate	+20%	71%	100
	-20%	71%	104.5

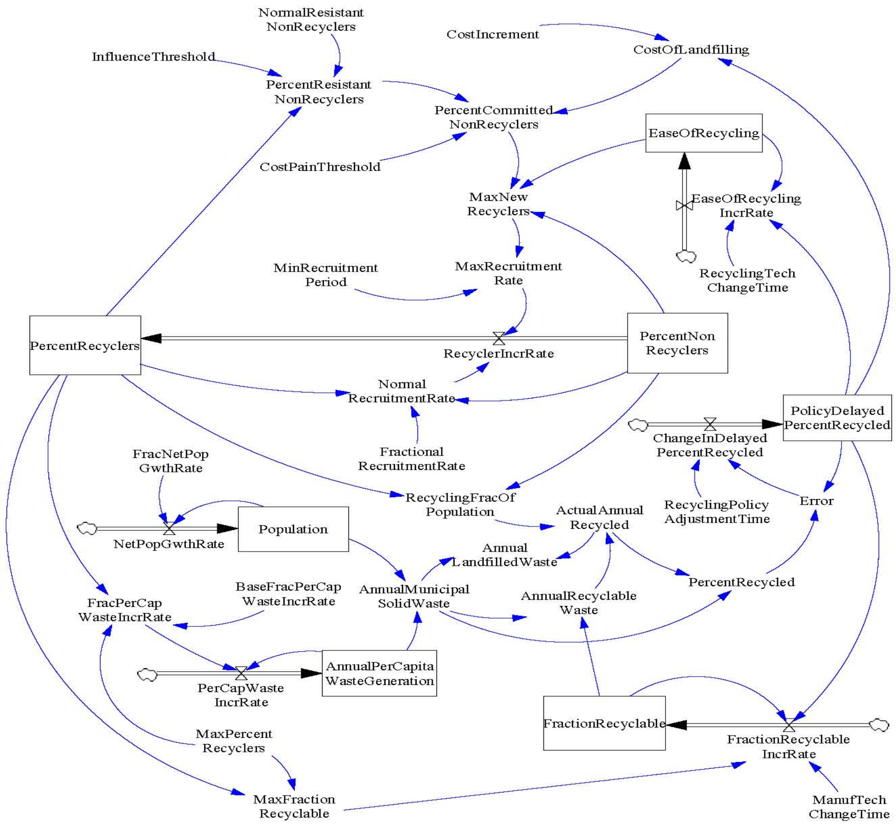


Figure 15: Case 7 model

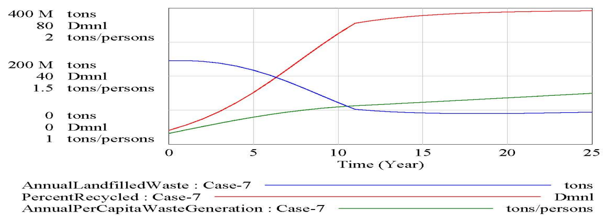


Figure 16: Case 7 results

Conclusions

Figure 17 below compares the results from all 7 models. The trend is clear – PercentRecycled increases (from 33% to over 70%) and AnnualLandfilledWaste decreases (from 272 million tons to about 100 million tons) for year 2000. The cumulative result of all the policy and social actions modeled in this exercise could have produced such a dramatic difference by year 2000 if they had been implemented in the early years of municipal recycling.

By year 2014, the final year shown in graphs, AnnualLandfilledWaste would rise to 459 million tons in a business-as-usual recycling scenario (Case 1), but actually drop to about 95 million tons when all policy and social actions are combined (Case 7).

By year 2050, the AnnualLandfilledWaste would jump to a whopping 1174 million tons in Case 1, compared to a modest 159 million tons in Case 7. This suggests the possibility of an order-of-magnitude reduction in the amount of waste landfilled annually over the next half century if serious action is taken now. This is, of course, insight about the problem and not prediction of precise outcomes for policy/social actions.

The final model in Case 7 includes all of the improvements and is therefore a fairly complicated model. But testing the model was not proportionately more difficult because I used an incremental approach to modifications/testing as I progressed from Case 1 to Case 7.

With this exercise, I have had the opportunity to put together all the pieces of the system dynamics methodology, walk through all the steps carefully, and produce results that, at least on the surface, look reasonable for purposes of generating insight. The results have largely been along the lines of my hypotheses. This has also given me a chance to reinforce my understanding of balancing and reinforcing feedbacks, exponential growth and S-shaped growth.

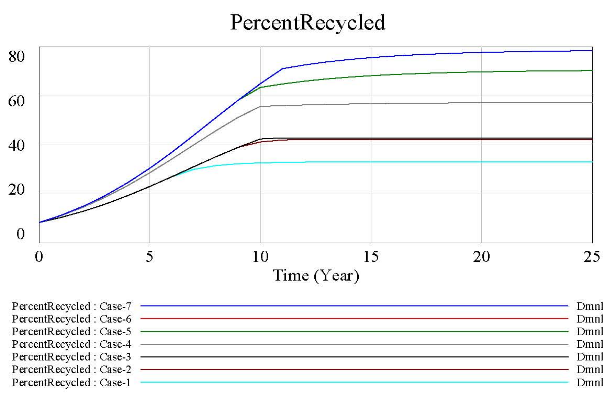
My only area of discomfort has to do with reference data. Obtaining the RBP was not a problem for the business-as-usual scenario in Case 1 and the validation for that case included comparison of the results with the reference data. But I had no way of getting any reasonable reference data for the policy and social actions that I was experimenting with on a speculative basis. The policy options that I have considered – linking landfill costs to recycling percentage, requiring rapid changes in recycling and manufacturing technologies, etc. – don't exist today and I couldn't find any similar or analogous situations. The social actions are even less likely to occur at the scale that I have assumed (unless there is a major change in society) and I couldn't think of any analogous situations from which I could construct some reference data. All I could really make sure was that each model enhancement was debugged, verified and sanity-checked as much as possible for correctness, including sensitivity analyses on key parameters. I have a reasonably high confidence level in all the models presented in this report.

Future work

There are two areas where additional modeling effort in the future would be worthwhile:

- Including a portion of the economy within the model boundary, so that factors influencing the prices of virgin raw materials and recycled materials can be modeled. In such an enhanced model, we could apply an environmental tax to increase the prices of virgin materials and see if this provides enough of an incentive for the population to recycle more. If the market works right, perhaps recyclers would be paid in this scenario for the value of the materials they provide! Such a plan would also be highly controversial and there might be interesting feedback effects due to different groups reacting to such a policy with self-interest.
- The real measure of our environmental stewardship is reflected in the total amount of energy and virgin raw materials used in the economy and unusable waste generated (including greenhouse gases) each year. To the extent that recyclable materials are transported long distances (as is common today), additional energy is used up and additional greenhouse gases are generated in the recycling process. This suggests that a life-cycle analysis is required to minimize overall waste (not limited to solid waste) and maximize resource efficiency[4]. This may open up more interesting scenarios to model.

[4] I wrote a newspaper article that argues for a simplified life-cycle analysis: K. Venkat, "Beware the life cycle of 'recycled'", The Christian Science Monitor, July 14, 2003 (http://www.csmonitor.com/2003/0714/p09s02-coop.html).



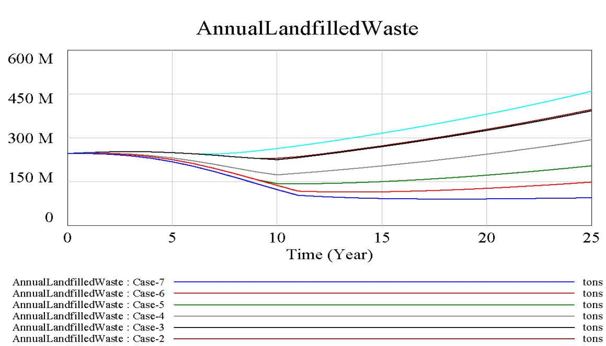


Figure 17: Comparison of Cases 1-7

Attachments

The attachments contain the Vensim model equations for three of the seven models presented in this report: the baseline model (Case 1), the model containing all of the policy actions (Case 4), and the final model containing all of the policy and social actions (Case 7).

Attachment 1: Vensim Model Equations for Case 1

```
(01)    ActualAnnualRecycled=
                AnnualRecyclableWaste * RecyclingFracOfPopulation
        Units: tons
(02)    AnnualLandfilledWaste=
                AnnualMunicipalSolidWaste - ActualAnnualRecycled
        Units: tons
(03)    AnnualMunicipalSolidWaste=
                AnnualPerCapitaWasteGeneration * Population
        Units: tons
(04)    AnnualPerCapitaWasteGeneration= INTEG (
                PerCapWasteIncrRate,
                        1.08)
        Units: tons/persons
(05)    AnnualRecyclableWaste=
                AnnualMunicipalSolidWaste * FractionRecyclable
        Units: tons
(06)    CostOfLandfilling=
                2500
        Units: dollars/tons
(07)    CostPainThreshold=
                5000
        Units: dollars/tons
(08)    EaseOfRecycling=
                0.5
        Units: Dmnl
(09)    FINAL TIME  = 25
        Units: Year
(10)    FracNetPopGwthRate=
                0.01
        Units: 1/Year
(11)    FracPerCapWasteIncrRate=
                0.028
        Units: 1/Year
(12)    FractionalRecruitmentRate=
                0.3
        Units: 1/Year
(13)    FractionRecyclable=
                0.55
        Units: Dmnl
(14)    INITIAL TIME  = 0
        Units: Year
```

(15) MaxNewRecyclers=
IF THEN ELSE(PercentNonRecyclers > PercentCommittedNonRecyclers, EaseOfRecycling
* (PercentNonRecyclers -
PercentCommittedNonRecyclers), 0)
Units: percentpersons
(16) MaxRecruitmentRate=
MaxNewRecyclers/MinRecruitmentPeriod
Units: percentpersons/Year
(17) MinRecruitmentPeriod=
1
Units: Year
(18) NetPopGwthRate=
Population * FracNetPopGwthRate
Units: persons/Year
(19) NormalRecruitmentRate=
FractionalRecruitmentRate * PercentNonRecyclers * (PercentRecyclers/(PercentRecyclers
+ PercentNonRecyclers))
Units: percentpersons/Year
slower growth initially when there are few recyclers; slower
growth at the end when there are few nonrecyclers; maximum
growth when enough recyclers and nonrecyclers so that
interactions are maximum
(20) PerCapWasteIncrRate=
AnnualPerCapitaWasteGeneration * FracPerCapWasteIncrRate
Units: tons/persons/Year
(21) PercentCommittedNonRecyclers=
IF THEN ELSE(CostOfLandfilling < CostPainThreshold, PercentResistantNonRecyclers
, (CostPainThreshold/CostOfLandfilling) * PercentResistantNonRecyclers)
Units: percentpersons
(22) PercentNonRecyclers= INTEG (
-RecyclerIncrRate,
85)
Units: percentpersons
(23) PercentRecycled=
(ActualAnnualRecycled/AnnualMunicipalSolidWaste) * 100
Units: Dmnl
(24) PercentRecyclers= INTEG (
RecyclerIncrRate,
15)
Units: percentpersons
(25) PercentResistantNonRecyclers=
40
Units: percentpersons
(26) Population= INTEG (
NetPopGwthRate,
2.48e+008)
Units: persons
(27) RecyclerIncrRate=
MIN(NormalRecruitmentRate, MaxRecruitmentRate)
Units: percentpersons/Year
(28) RecyclingFracOfPopulation=
PercentRecyclers/(PercentRecyclers + PercentNonRecyclers)
Units: Dmnl

(29) SAVEPER =
TIME STEP
Units: Year [0,?]
(30) TIME STEP = 1
Units: Year [0,?]

Attachment 2: Vensim Model Equations for Case 4

(01) ActualAnnualRecycled=
AnnualRecyclableWaste * RecyclingFracOfPopulation
Units: tons

(02) AnnualLandfilledWaste=
AnnualMunicipalSolidWaste - ActualAnnualRecycled
Units: tons
(03) AnnualMunicipalSolidWaste=
AnnualPerCapitaWasteGeneration * Population
Units: tons
(04) AnnualPerCapitaWasteGeneration= INTEG (
PerCapWasteIncrRate,
1.08)
Units: tons/persons
(05) AnnualRecyclableWaste=
AnnualMunicipalSolidWaste * FractionRecyclable
Units: tons
(06) ChangeInDelayedPercentRecycled=
Error/RecyclingPolicyAdjustmentTime
Units: 1/Year
(07) CostIncrement=
100
Units: dollars/tons
(08) CostOfLandfilling=
2500 + (100 - PolicyDelayedPercentRecycled) * CostIncrement
Units: dollars/tons
(09) CostPainThreshold=
5000
Units: dollars/tons
(10) EaseOfRecycling= INTEG (
EaseOfRecyclingIncrRate,
0.5)
Units: Dmnl
(11) EaseOfRecyclingIncrRate=
MIN(1-EaseOfRecycling, (1 -
PolicyDelayedPercentRecycled/100)/EaseOfRecycling
)/RecyclingTechChangeTime
Units: 1/Year
(12) Error=
PercentRecycled - PolicyDelayedPercentRecycled
Units: Dmnl
(13) FINAL TIME = 25
Units: Year
(14) FracNetPopGwthRate=
0.01
Units: 1/Year

(15) FracPerCapWasteIncrRate=
0.028
Units: 1/Year
(16) FractionalRecruitmentRate=
0.3
Units: 1/Year
(17) FractionRecyclable= INTEG (
FractionRecyclableIncrRate,
0.55)
Units: Dmnl
(18) FractionRecyclableIncrRate=
IF THEN ELSE(FractionRecyclable < MaxFractionRecyclable,
MIN(MaxFractionRecyclable
- FractionRecyclable, (1 - PolicyDelayedPercentRecycled/100)/FractionRecyclable
)/ManufTechChangeTime, 0)
Units: 1/Year
MIN(1-EaseOfRecycling, (1 -
DisseminatedPercentRecycledValue/100)/EaseOfRecycling)/RecyclingT
echChangeTime
(19) INITIAL TIME = 0
Units: Year
(20) ManufTechChangeTime=
5
Units: Year
(21) MaxFractionRecyclable=
0.75
Units: Dmnl
(22) MaxNewRecyclers=
IF THEN ELSE(PercentNonRecyclers > PercentCommittedNonRecyclers,
EaseOfRecycling
* (PercentNonRecyclers -
PercentCommittedNonRecyclers), 0)
Units: percentpersons
(23) MaxRecruitmentRate=
MaxNewRecyclers/MinRecruitmentPeriod
Units: percentpersons/Year
(24) MinRecruitmentPeriod=
1
Units: Year
(25) NetPopGwthRate=
Population * FracNetPopGwthRate
Units: persons/Year
(26) NormalRecruitmentRate=
FractionalRecruitmentRate * PercentNonRecyclers *
(PercentRecyclers/(PercentRecyclers
+ PercentNonRecyclers))
Units: percentpersons/Year
(27) PerCapWasteIncrRate=
AnnualPerCapitaWasteGeneration * FracPerCapWasteIncrRate
Units: tons/persons/Year
(28) PercentCommittedNonRecyclers=
IF THEN ELSE(CostOfLandfilling < CostPainThreshold,
PercentResistantNonRecyclers
, (CostPainThreshold/CostOfLandfilling
) * PercentResistantNonRecyclers)
Units: percentpersons

(29) PercentNonRecyclers= INTEG (
-RecyclerIncrRate,
85)
Units: percentpersons
(30) PercentRecycled=
(ActualAnnualRecycled/AnnualMunicipalSolidWaste) * 100
Units: Dmnl
(31) PercentRecyclers= INTEG (
RecyclerIncrRate,
15)
Units: percentpersons
(32) PercentResistantNonRecyclers=
40
Units: percentpersons
(33) PolicyDelayedPercentRecycled= INTEG (
ChangeInDelayedPercentRecycled,
25)
Units: Dmnl
(34) Population= INTEG (
NetPopGwthRate,
2.48e+008)
Units: persons
(35) RecyclerIncrRate=
MIN(NormalRecruitmentRate, MaxRecruitmentRate)
Units: percentpersons/Year
(36) RecyclingFracOfPopulation=
PercentRecyclers/(PercentRecyclers + PercentNonRecyclers)
Units: Dmnl
(37) RecyclingPolicyAdjustmentTime=
2
Units: Year
(38) RecyclingTechChangeTime=
2
Units: Year
(39) SAVEPER =
TIME STEP
Units: Year [0,?]
(40) TIME STEP = 1
Units: Year [0,?]

Attachment 3: Vensim Model Equations for Case 7

(01) ActualAnnualRecycled=
AnnualRecyclableWaste * RecyclingFracOfPopulation
Units: tons
(02) AnnualLandfilledWaste=
AnnualMunicipalSolidWaste - ActualAnnualRecycled
Units: tons
(03) AnnualMunicipalSolidWaste=
AnnualPerCapitaWasteGeneration * Population
Units: tons
(04) AnnualPerCapitaWasteGeneration= INTEG (
PerCapWasteIncrRate,
1.08)

Units: tons/persons
(05) AnnualRecyclableWaste=
AnnualMunicipalSolidWaste * FractionRecyclable
Units: tons
(06) BaseFracPerCapWasteIncrRate=
0.028
Units: 1/Year
(07) ChangeInDelayedPercentRecycled=
Error/RecyclingPolicyAdjustmentTime
Units: 1/Year
(08) CostIncrement=
100
Units: dollars/tons
(09) CostOfLandfilling=
2500 + (100 - PolicyDelayedPercentRecycled) * CostIncrement
Units: dollars/tons
(10) CostPainThreshold=
5000
Units: dollars/tons
(11) EaseOfRecycling= INTEG (
EaseOfRecyclingIncrRate,
0.5)
Units: Dmnl
(12) EaseOfRecyclingIncrRate=
MIN(1-EaseOfRecycling, (1 -
PolicyDelayedPercentRecycled/100)/EaseOfRecycling
)/RecyclingTechChangeTime
Units: 1/Year
(13) Error=
PercentRecycled - PolicyDelayedPercentRecycled
Units: Dmnl
(14) FINAL TIME = 25
Units: Year
(15) FracNetPopGwthRate=
0.01
Units: 1/Year
(16) FracPerCapWasteIncrRate=
BaseFracPerCapWasteIncrRate * (1 - PercentRecyclers/MaxPercentRecyclers)
Units: 1/Year
(17) FractionalRecruitmentRate=
0.3
Units: 1/Year
(18) FractionRecyclable= INTEG (
FractionRecyclableIncrRate,
0.55)
Units: Dmnl
(19) FractionRecyclableIncrRate=
IF THEN ELSE(FractionRecyclable < MaxFractionRecyclable,
MIN(MaxFractionRecyclable
- FractionRecyclable, (1 - PolicyDelayedPercentRecycled/100)/FractionRecyclable
)/ManufTechChangeTime, 0)
Units: 1/Year
MIN(1-EaseOfRecycling, (1 -
DisseminatedPercentRecycledValue/100)/EaseOfRecycling)/RecyclingT
echChangeTime
(20) InfluenceThreshold=

50
Units: percentpersons
(21) INITIAL TIME = 0
Units: Year
(22) ManufTechChangeTime=
5
Units: Year
(23) MaxFractionRecyclable=
0.75 + 0.25 * PercentRecyclers/MaxPercentRecyclers
Units: Dmnl
(24) MaxNewRecyclers=
IF THEN ELSE(PercentNonRecyclers > PercentCommittedNonRecyclers, EaseOfRecycling
* (PercentNonRecyclers -
PercentCommittedNonRecyclers), 0)
Units: percentpersons
(25) MaxPercentRecyclers=
100
Units: percentpersons
(26) MaxRecruitmentRate=
MaxNewRecyclers/MinRecruitmentPeriod
Units: percentpersons/Year
(27) MinRecruitmentPeriod=
1
Units: Year
(28) NetPopGwthRate=
Population * FracNetPopGwthRate
Units: persons/Year
(29) NormalRecruitmentRate=
FractionalRecruitmentRate * PercentNonRecyclers * (PercentRecyclers/(PercentRecyclers
+ PercentNonRecyclers))
Units: percentpersons/Year
(30) NormalResistantNonRecyclers=
40
Units: percentpersons
(31) PerCapWasteIncrRate=
AnnualPerCapitaWasteGeneration * FracPerCapWasteIncrRate
Units: tons/persons/Year
(32) PercentCommittedNonRecyclers=
IF THEN ELSE(CostOfLandfilling < CostPainThreshold, PercentResistantNonRecyclers
, (CostPainThreshold/CostOfLandfilling
) * PercentResistantNonRecyclers)
Units: percentpersons
(33) PercentNonRecyclers= INTEG (
-RecyclerIncrRate,
85)
Units: percentpersons
(34) PercentRecycled=
(ActualAnnualRecycled/AnnualMunicipalSolidWaste) * 100
Units: Dmnl
(35) PercentRecyclers= INTEG (
RecyclerIncrRate,
15)
Units: percentpersons

(36) PercentResistantNonRecyclers=
IF THEN ELSE(PercentRecyclers > InfluenceThreshold,
NormalResistantNonRecyclers
* InfluenceThreshold/PercentRecyclers, NormalResistantNonRecyclers)
Units: percentpersons
(37) PolicyDelayedPercentRecycled= INTEG (
ChangeInDelayedPercentRecycled,
25)
Units: Dmnl
(38) Population= INTEG (
NetPopGwthRate,
2.48e+008)
Units: persons
(39) RecyclerIncrRate=
MIN(NormalRecruitmentRate, MaxRecruitmentRate)
Units: percentpersons/Year
(40) RecyclingFracOfPopulation=
PercentRecyclers/(PercentRecyclers + PercentNonRecyclers)
Units: Dmnl
(41) RecyclingPolicyAdjustmentTime=
2
Units: Year
(42) RecyclingTechChangeTime=
2
Units: Year
(43) SAVEPER =
TIME STEP
Units: Year [0,?]
(44) TIME STEP = 1
Units: Year [0,?]