Forecasting municipal solid waste generation in a fast-growing urban region with system dynamics modeling

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Abstract

Both planning and design of municipal solid waste management systems require accurate prediction of solid waste generation. Yet achieving the anticipated prediction accuracy with regard to the generation trends facing many fast-growing regions is quite challenging. The lack of complete historical records of solid waste quantity and quality due to insufficient budget and unavailable management capacity has resulted in a situation that makes the long-term system planning and/or short-term expansion programs intangible. To effectively handle these problems based on limited data samples, a new analytical approach capable of addressing socioeconomic and environmental situations must be developed and applied for fulfilling the prediction analysis of solid waste generation with reasonable accuracy. This study presents a new approach – system dynamics modeling – for the prediction of solid waste generation in a fast-growing urban area based on a set of limited samples. To address the impact on sustainable development city wide, the practical implementation was assessed by a case study in the city of San Antonio, Texas (USA). This area is becoming one of the fastest-growing regions in North America due to the economic impact of the North American Free Trade Agreement (NAFTA). The analysis presents various trends of solid waste generation associated with five different solid waste generation models using a system dynamics simulation tool – Stella®. Research findings clearly indicate that such a new forecasting approach may cover a variety of possible causative models and track inevitable uncertainties down when traditional statistical least-squares regression methods are unable to handle such issues.

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1. Introduction

The prediction of municipal solid waste generation plays an important role in a solid waste management. Yet achieving the anticipated prediction accuracy with regard to the generation trends facing many fast-growing regions is quite challenging. In addition to population growth and migration, underlying economic development, household size, employment changes, and the impact of waste recycling would influence the solid waste generation interactively. The development of a reliable model for predicting the aggregate impact of economic trend, population changes, and recycling impact on solid waste generation would be a useful advance in the practice of solid waste management.

Traditional forecasting methods for solid waste generation frequently count on the demographic and socio-economic factors on a per-capita basis. The per-capita coefficients may be taken as fixed over time or they may be projected to change with time. Grossman et al. (1974) extended such considerations by including the effects of population, income level, and the dwelling unit size in a linear regression model. Niessen and Alsobrook (1972) conducted similar estimates by providing some other extensive variables characterizing waste generation. But dynamic properties in the process of solid waste generation cannot be fully characterized in those model formulations. Econometric forecasting, one of
the alternatives to static models, is an approach in which the future forecasts are derived from current forecasts of the independent variables themselves (Chang et al., 1993). It covers part of the dynamic features in forecasting analysis. When recycling impact is phenomenal, intervention analysis may account for the varying trends of solid waste generation under uncertainty (Chang and Lin, 1997). Such an analysis creates profound impacts in dealing with the possible structure change of solid waste generation trends in metropolitan regions. To implement those traditional statistical forecasting methods, however, it would require collecting thorough socioeconomic and environmental information before the forecasting analysis can be performed. In many cases, municipalities might not have sufficient budget and management capacity to maintain a complete database of solid waste quantity and quality in support of such needs on a long-term basis.

Most traditional statistical forecasting models, such as the geometry average method, saturation curve method, least-squares regression method, and the curve extension method, are designed based on the configuration of semi-empirical mathematical models. The structure of these models is simply an expression of cause-effect or an illustration of trend extension in order to verify the inherent systematic features that are recognized as related to the observed database. In light of the evolution of structured or semi-structured forecasting techniques, the synergy of fuzzy forecasting and grey dynamic modeling is viewed as a promising approach for handling forecasting issues under uncertainty. The grey dynamic model was developed earlier simply to resolve the data scarcity issue (Deng, 1982). It is particularly designed for handling situations in which only limited data are available for forecasting practice and system environments are not well-defined or fully understood. In conjunction with fuzzy regression analysis, a revised dynamic forecasting method – grey fuzzy dynamic modeling – that is suitable for the situation when only very limited samples are available for forecasting practice, was demonstrated to handle the dynamic prediction analysis of municipal solid waste generation with reasonable accuracy (Chen and Chang, 2000).

When the database is not sufficient to support traditional statistical forecasting analyses yet ample enough to run several grey dynamic models with different natures, there is a need to integrate those separate dynamic efforts as a whole that may be able to account for the interrelationships among relevant dynamic features influential for municipal solid waste generation. Such concatenation enables us to explore the interactions among a variety of socio-economic, environmental, and managerial factors when we still have to handle the data scarcity issue. This study presents a new approach – system dynamic modeling – for the prediction of municipal solid waste generation in an urban area based on a set of limited samples. To address the impact on sustainable development city wide, the practical implementation was accessed by a case study in the city of San Antonio, Texas (USA), which is one of the fast-growing regions in North America. It presents various trends of municipal solid waste generation associated with five different solid waste generation models using a system dynamics simulation tool – Stella®. Discrepancies embedded in the prediction matrix based on those models may provide obvious clues in a form of interval number to address possible ranges of uncertainty in municipal solid waste generation.

2. Methodology

The method of system thinking has been used for over 30 years (Forrester, 1961). It provides us with effective tools for better understanding those large-scale complex management problems. System dynamics, being designed based on system thinking, is a well-established methodology for studying and managing complex feedback systems. It requires constructing the unique “causal loop diagrams” or “stock and flow diagram” to form a system dynamics model for applications. Relevant work of how to develop system dynamics models can be found in the literature (Forrester, 1961, 1968; Randers, 1980; Richardson and Pugh, 1981; Mohapatra, 1994).

To build a system dynamics model, one should identify a problem and develop a dynamic hypothesis explaining the cause of the problem. The mode formulation is normally designed to test a computer simulation model with regard to alternative policies in the problem. Simulation runs in a system dynamics model is governed entirely by the passage of time. Such a time-step simulation analysis takes a number of simulation steps along the timeframe to update the status of system variables of concern as a result of system activities. When the initial conditions are assigned for those variables, which denote the state of the system, the model may start to produce the related consequences for those system variables based on the initiation of action and the flow of information.

System dynamics modeling has been used to address practically every sort of feedback system, including business systems (Sterman, 2000), ecological systems (Grant et al., 1997), socio-economic systems (Forrester, 1969, 1971; Meadows, 1973), agricultural systems (Qu and Barney, 1998; Saysel et al., 2002), political decision-making systems (Nail et al., 1992), and environmental systems (Vizayakumar and Mohapatra, 1991, 1993; Vezjak et al., 1998; Ford, 1999; Wood and Shelley, 1999; Abbott and Stanley, 1999; Deaton and Winebrake, 2000; Guo et al., 2001). In terms of environmental concerns, the application matrix has covered several issues,
including environmental impact analysis of coalfields (Vizayakumar and Mohapatra, 1991, 1993), lake eutrophication assessment (Vezjak, 1998), pesticide control (Ford, 1999), wetland metal balance (Wood and Shelley, 1999), groundwater recharge (Abbott and Stanley, 1999), lake watershed management (Guo et al., 2001), river pollution control (Deaton and Winebrake, 2000), and solid waste management (Mashayekhi, 1993; Sudhir et al., 1997; Karavezyris et al., 2002). Within the solid waste management regime, Mashayekhi (1993) explored a dynamic analysis for analyzing the transition in the New York State solid waste system. Sudhir et al. (1997) further employed a system dynamics model to capture the dynamic nature of interactions among the various components in the urban solid waste management system, and Karavezyris et al. (2002) developed a methodology to incorporate qualitative variables such as voluntary recycling participation and regulation impact quantitatively. The model provides a platform for examination of various structural and policy alternatives for sustainable solid waste management. More applications in different topical areas can be found in System Dynamics Review (Abbott and Stanley, 1999).

Most computer simulation applications using system dynamics models rely on the use of the software Vensim® and Stella®, in which the mechanisms of system dynamics can be handled by a user-friendly interface. These model development procedures are designed based on a visualization process that allows model builders to conceptualize, document, simulate, and analyze models of dynamic systems. They offer a flexible way for building a variety of simulation models from causal loops or stock and flow. The dynamic relationships between the elements, including variables, parameters, and their linkages, can be created onto the interface using user-friendly visual tools. The feedback loops associated with these employed variables can be visualized at every step throughout the modeling process. Simulation runs are carried out entirely along the prescribed timeline. At the end, some designated system variables of interest are brought up to date for demonstration and policy evaluation.

While dynamic systems models may of necessity be complex, their complexity is achieved through combinations of simpler sub-models linked to simulate the system in question. These sub-models are themselves dynamic systems models exhibiting specific systems behaviors such as linear, exponential, and logistic growth or decay, overshoot and collapse, and oscillation (Deaton and Winebrake, 2000). In the present study, the dynamic models presented characterize solid waste generation as exhibiting the behavior of linear growth. In these models the concept of feedback within the system is not explored due to the difficulty of linking waste generation per se directly back to consumption activities.

3. Case study

3.1. Overview of the study area

NAFTA is a comprehensive trade agreement that improves virtually all aspects of doing business within North America after being implemented on January 1, 1994. Tremendous economic growth along the US-Mexico border region has been observed since then. Growth associated with population increases in Mexico (the Maquiladoras), and in the US (the river corridor along Laredo, McAllen, and Brownsville) very recently due to NAFTA related activities is apparent in the Rio Grande/ Rio Bravo region. Active economic activities due to the impact of NAFTA have been fast extended from the US-Mexico border region to the Harlingen, San Antonio, and Corpus Christi areas in Texas. In 1995, due to the increasing trend of municipal solid waste generation, the City of San Antonio implemented a voluntary recycling program to help reduce the amount of waste being landfilled; thus extending the life of the landfills. Revenue generated from the sale of recycled material would be expected to offset the operating costs. However, due to poor participation from the city residents, not enough income was generated to justify the continued operation of the recycling program. Ending the program, however, would shorten the lifespan of the landfills; therefore the City is considering building a material recovery facility (MRF) to continue the recycling program without requiring the support of the city residents.

For solid waste collection purposes, the City of San Antonio is divided into four service areas (see Fig. 1); Northloop, Northwest, Southcentral and Southeast. Solid waste is collected in each service area and sent to
a service center in that area. From the service center, the waste is transferred to three landfills/transfer stations. With the implementation of a material recycling facility some or all of the collected solid waste would be first routed from a service center or community drop-off station to the MRF where mechanical separation of recyclable material would ensue. Remaining unrecyclable material would then be routed to the landfills. Two potential locations for siting the proposed MRF are indicated in Fig. 1. To plan the capacity of the MRF, it is necessary to perform an accurate estimation of the amount of solid waste to be generated in the City of San Antonio by the year 2010 (i.e., the target year in planning).

3.2. System complexity

Simulation of municipal solid waste generation is predicated based on the contributing factors of population growth, household income, people per household, and economic activity. Dennison et al. (1995) found that waste generation on a per capita basis is inversely related to household size. Sudhir et al. (1997) described the links between these parameters and municipal solid waste generation as follows: economic activity and population growth affect household income and household income impacts per capita waste generation; and higher income households tend to produce higher amounts of waste (Sudhir et al., 1997). But it is believed that higher income households tend to achieve higher participation rates of recycling. For example, Saltzman et al. (1993) found a positive relationship with rising income and newspaper recycling and Schultz et al. (1995) in a review article cite numerous studies reporting a significant positive relationship between rising income and increased recycling effort. The situation could be further complicated if there is a recycling program underway that is mandated by law or regulation. Considering interactions among a number of related social, economic, and environmental factors.

### Table 1

| US Census data for San Antonio allocated into solid waste collection service centers |
|------------------------|-----------------|-----------------|-------------|-------------|
|                        | Population count | Median income H/hold | CPI-2000 | Avg capita/H | Tonnes count |
| 1980 Census SF-3 by census tract |
| Northloop service center | 232,177          | $18,734          | $39,150  | 2.71        | 38,745       |
| Northwest service center | 144,791          | $16,461          | $34,400  | 3.13        | 45,665       |
| Southcentral service center | 232,550         | $9436            | $19,719  | 3.61        | 37,362       |
| Southeast service center | 176,505          | $10,194          | $21,302  | 3.10        | 33,211       |
| Total population       | 786,023          |                  |          |             | 154,983      |
| 1990 Census SF-3 by census tract |
| Northloop service center | 308,511          | $32,589          | $49,737  | 2.31        | 56,756       |
| Northwest service center | 210,494          | $28,445          | $34,400  | 3.13        | 66,809       |
| Southcentral service center | 239,102         | $15,921          | $20,976  | 3.14        | 54,728       |
| Southeast service center | 177,827          | $17,721          | $22,900  | 2.57        | 48,648       |
| Total population       | 935,933          |                  |          |             | 227,021      |
| 2000 Census SF-3 by census tract |
| Northloop service center | 411,417          | $48,791          | $48,791  | 2.55        | 74,620       |
| Northwest service center | 290,135          | $43,156          | $43,156  | 2.83        | 77,945       |
| Southcentral service center | 258,969         | $25,477          | $25,477  | 3.45        | 54,789       |
| Southeast service center | 183,215          | $27,428          | $27,428  | 2.92        | 63,690       |
| Total population       | 1,144,646        |                  |          |             | 298,478      |

environmental, managerial, geographical, and regulatory factors may further compound such an understanding. They are complex not only because all factors are simultaneously involved and affected by each other but because they dynamically occur over time.

To develop a predictive statistical regression model for the four service center areas we will have to rely on the historical population and income data provided by the US Census for the years, 1980, 1990, and 2000 only. However, statistical issues, specifically a small degree of freedom, prohibits trying to include more than two explanatory variables in the model due to the scarcity of datasets. With no other reliable databases available in this case it requires employing a system dynamics model to project the amount of waste generated up to the year 2010 so as to help analyze the implications of different MRF site selection alternatives in the near future.

Table 4
Simulation models used to estimate the solid waste generation in 2010 (tonnes/year)

<table>
<thead>
<tr>
<th>Models</th>
<th>Driving factor in generation/service center</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Total income per service center</td>
</tr>
<tr>
<td>2</td>
<td>People per household</td>
</tr>
<tr>
<td>3</td>
<td>Historical amount generated</td>
</tr>
<tr>
<td>4</td>
<td>Income per household</td>
</tr>
<tr>
<td>5</td>
<td>Population</td>
</tr>
</tbody>
</table>

Fig. 3. Generalized form of model 1 used to simulate tonnes generated by income per service center.
3.3. Data collection and analysis

Population and average people per household data for the years 1980, 1990, and 2000 were collected by census tract from the US Census Bureau (Census, 2003). The city of San Antonio allocated the census tracts to the appropriate service center. Data for median household income was likewise allocated yielding values for population, median household income, and people per household according to each of the four service center

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**Fig. 4.** Generalized form of model 2 used to simulate tonnes generated by people per household.

**Fig. 5.** Generalized form of model 3 used to simulate tonnes generated by historical amount generated.

**Fig. 6.** Generalized form of model 4 used to simulate tonnes generated by income per household.
regions (BLS, 2003). Per capita income and population growth in Texas were further predicted based on the increasing trend of economic growth due to the impact of NAFTA (NAFTA (2000)) and related employment growth (BLS, 2003).

Plotting the data indicated a linear relationship with time. A linear trend was fit to the data using the least squares method by simple linear regression analysis. The values of population, median income per household, population per household, and tonnes of waste collected were regressed individually versus time for the three US Census periods of 1980, 1990, and 2000 (see Table 1). Also tested were the calculated relationships of income per service center, tonnes of waste

### Table 5
Simulation results for municipal solid waste generation in San Antonio (tonnes/year)

<table>
<thead>
<tr>
<th>Model</th>
<th>Northeast</th>
<th>Southeast</th>
<th>Southcentral</th>
<th>Northwest</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base case</td>
<td>93,833</td>
<td>65,355</td>
<td>75,058</td>
<td>113,449</td>
<td>347,675</td>
</tr>
<tr>
<td>1</td>
<td>88,238</td>
<td>93,483</td>
<td>89,319</td>
<td>95,085</td>
<td>366,125</td>
</tr>
<tr>
<td>2</td>
<td>90,761</td>
<td>77,825</td>
<td>87,984</td>
<td>105,379</td>
<td>361,949</td>
</tr>
<tr>
<td>3</td>
<td>92,550</td>
<td>79,333</td>
<td>89,251</td>
<td>109,077</td>
<td>370,210</td>
</tr>
<tr>
<td>4</td>
<td>96,481</td>
<td>82,875</td>
<td>93,224</td>
<td>113,748</td>
<td>386,328</td>
</tr>
<tr>
<td>5</td>
<td>127,912</td>
<td>80,208</td>
<td>91,773</td>
<td>108,316</td>
<td>408,209</td>
</tr>
<tr>
<td>Disparity</td>
<td>39,674</td>
<td>15,658</td>
<td>18,139</td>
<td>18,663</td>
<td>46,260</td>
</tr>
</tbody>
</table>

Fig. 7. Generalized form of model 5 used to simulate tonnes generated by population.

Fig. 8. Solid waste generation simulation as a function of population (model 5).
generated normalized to income, tonnes generated per capita, tonnes generated per household income, and tonnes generated per household population. With only three data points, normality is not assumed nor is causality sought but rather an indication of trend by goodness of fit. In all cases $r^2$ values ranged from 0.89 to 0.99 except for the population per household relationship ($r^2$ range is 0.11–0.31). The slope of the regressed line was used as the annual growth rate in the model. NAFTA-related rate converters were developed by determining: (1) the average rate of increase in employment growth factored into the population growth rate (see Tables 2 and 3) the average rate of increase in sales from exports to NAFTA partners factored into the income per sector growth rate (see Table 3).

### 3.4. System dynamics modeling

The software package Stella® was used to perform the simulations, which is iconographic software using basic building blocks such as stocks, flows, and converters (see Fig. 2) that are intuitively assembled to simulate the dynamic processes of a system. Stocks represent the accounting of a system component, either spatially or temporally (i.e., population, waste generated); flows are the rate at which the component flows in or out of the stock; and converters modify rates of change and unit conversions.

Solid waste generation simulation was performed for each service sector in this study. The predicted amount of waste generated was simulated using five models. Each model simulated solid waste generation (tonnes/year) as a function of the various factors previously mentioned (see Table 4). For this simulation, tonnes generated are represented as a product of two stocks, rate of generation is a flow, and the economic effect of NAFTA is shown as a converter. Figs. 3–7 illustrate the generalized form of the model used to estimate waste generation. Each model was run for all service centers with a time step of 1 year.

For each model, the ratio of tonnes generated to the driving factor (i.e., population) was established for each period of record (1980, 1990, and 2000), and regressed to find the growth rate for the ratio. This was done to establish the effect on waste generation due to the factor in question. Year 2000 values were taken for initial values in the stocks and used to project results yearly until the year 2010. Total tonnes generated were calculated by multiplying Tonnes per Population by Population. A yearly recycling rate was developed by comparing tonnes recycled vs. tonnes of waste collected from the years 1995–2002 and multiplied by the simulated amount of tonnes generated to estimate the amount of waste recycled under current conditions.

### 3.5. Results and discussions

The simulated results for waste generation in the year 2010 for the four service centers are shown in Table 5. The estimated amount of waste generation...
from regression analysis in terms of population is also provided as a base case for the purpose of comparison. The estimates are listed in order of increasing tonnage. The last row in Table 5 lists the range of projected values based on the five models proposed in system dynamics modeling. These five interval numbers constitute a prediction matrix that potentially reflects the uncertainties in decision-making. Model 1 or 2 tends to generate more lower bounds and model 4 or 5 tends to produce more upper bounds than the others. The reliability of predicted values obtained from regression analysis is varying over the different service areas. It exhibits a potential of underestimation in the Southeast and South-central service areas as compared those with interval numbers.

The disparity in the extremes of the estimates indicates that it is important to choose the most appropriate model to prevent over-or under-estimation of tonnage generated. Models 2, 3, 4, and 5 are functions of single factors and exhibit similar linear growth patterns such as in Fig. 8. Model 1 (Tonnes per Income), however, exhibits slightly different behavior (see Fig. 9). While all the service center regions exhibit waste generation increases, the behavior of the increase is markedly different. The change in average number of people per household is different than the other factors that affect waste generation. Average number of people per household is decreasing over time while all other factors are increasing. This effect is accounted for in the tonnes per income model. The only model that incorporates all of the driving factors of population, people per household, income per household and economic activity is model 1; therefore, it best reflects the dynamics of the system.

This analysis thus concluded that model 1 might be selected as the most appropriate model to reflect the system dynamics in solid waste generation. Table 6 lists model 1 with the simulated amount of waste generated in 2010 per service center and the amount of simulated waste recycled under the current recycling system. The recycled amounts of waste in this simulation will be viewed as the basic amounts as long as the private recycling market is still active. Fig. 10 summarizes historical records and predictive results of San Antonio population, income, household size, and waste generation. The increasing trend is phenomenal in all four aspects.

The greatest increase in population by service center has and will continue to occur in the Northloop and Northwest service centers (Fig. 10). Median income shows a steady increase over time with the ratio relative to service center remaining the same for all service centers. The average persons per household exhibits some fluctuation over the past twenty years with a slight decreasing trend evident in the Northloop and Northwest service centers. It is this effect, the decrease in persons per household in the Northloop and Northwest service centers, that accounts for the relative increase in solid waste generation in the Southcentral and Southeast service centers in the 2010 projections.

4. Conclusion

In this analysis, system dynamics models were developed for the prediction of solid waste generation in an urban setting having a high economic growth potential. A case study for the City of San Antonio, Texas
presented its unique solutions based on system dynamics outputs. Five planning models were considered based on different types of system dynamics models, while the base case was designed according to a traditional regression analysis. All of the five planning models were based on an assumption that the existing recycling pattern through the private sector will remain in the entire planning horizon. Thus, the system will constantly maintain a minimum level of recycling accomplishment although participation in public recycling programs remains inactive. Interactions among several system components within a prescribed time frame were examined dynamically via the use of software package Stella®.

The models simulated five different combinations of factors that influence solid waste generation. The disparity in the extremes of the estimates indicates that it is important to choose the most appropriate model to prevent over- or under-estimation of tonnage generated. Model 1 was chosen as the representative estimation for this reason as well as its incorporation of all possible driving factors. But the disparity in the extremes of the estimates indicates that systematic uncertainty embedded in the estimation is influential. Based on the historical records and predictive results of San Antonio population, income, and waste generation, it can be concluded that the increasing trend is phenomenal in all aspects. The modeling results are directly useful for associated system planning with regard to site selection and capacity planning of MRF in the near future.

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