A system dynamic modeling approach for evaluating municipal solid waste generation, landfill capacity and related cost management issues

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A B S T R A C T

As planning for sustainable municipal solid waste management has to address several inter-connected issues such as landfill capacity, environmental impacts and financial expenditure, it becomes increasingly necessary to understand the dynamic nature of their interactions. A system dynamics approach designed here attempts to address some of these issues by fitting a model framework for Newark urban region in the US, and running a forecast simulation. The dynamic system developed in this study incorporates the complexity of the waste generation and management process to some extent which is achieved through a combination of simpler sub-processes that are linked together to form a whole. The impact of decision options on the generation of waste in the city, on the remaining landfill capacity of the state, and on the economic cost or benefit actualized by different waste processing options are explored through this approach, providing valuable insights into the urban waste-management process.

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1. Introduction

The study and management of complex processes such as the waste–management system often involve sophisticated interactions with the system components, the most far-reaching being raw material extraction and the most immediate being the associated environmental effects, financial expenditure and use of land resources used for treatment (e.g., landfill space). It is known that inadequate understanding of the dynamics of complicated information-feedback systems could render intuitive judgment about policy changes unreliable (Forrester, 1969). As planning for sustainable solid waste management has to address several inter-connected components, it becomes increasingly necessary to understand the dynamic nature of their interactions. Since many policy measures are made independent of a proper understanding of actual causal variables that are intertwined and interlinked as a connected whole, the risks of errors and oversight are often accenteduated. The waste–management system being no exception, a concise systems model for a city-scale process was developed here to address some of the major problems associated with assessing future scenarios.

System dynamics processing helps to conceptualize and rationally analyze the structure, interactions and mode of behavior of complex systems and sub-systems to explore, assess, and prognosticate their impacts in an integrated, holistic manner. It facilitates a more sophisticated, quantitative simulation than simple spread-sheet programs, and is capable of more robust and reliable outcomes (Wolstenholme, 2005). Since its conception in the 1960s several studies have used the system dynamic approach to address or simulate scenarios in a large number of different applications such as in urban dynamics (Forrester, 1969; Steiss, 1974a,b), global environmental sustainability (Meadows, 2004), corporate planning (Lyneis, 1980), for health care policies and programs (Royston et al., 1999), for analyzing city problems and development response to policy interventions (Satsangi et al., 2003) improving intervention policies to address epidemics (Ritchie-Dunham and Galvan, 1999), for predicting snow-melt in prairie-watersheds (Li and Simonovic, 2002) and even as a decision support tool for sustainable coral reef management (Chang et al., 2008). In the area of urban solid waste management, contributions using system dynamics have seen applications in planning for developing countries including the informal sector (Sudhir et al., 1997), transition from landfill method of disposal, and the pattern of annual expenses associated in a developed urban region (Mashayekhi, 1993), prediction of solid waste generation (Sufian and Bala, 2007; Dyson and Chang, 2005), forecasting municipal solid waste (MSW) using system dynamics and fuzzy logic (Karaveyris et al., 2002), testing proposition about linkages between ecological-spatial characteristics and solid waste management (Cummings and Cayer, 1993), strategic planning of construction and demolition waste management (Hao et al., 2007). The system dynamic study presented here is based on a predictive decision support tool for waste prognosis which utilizes demographic and socio-economic parameter values from studies carried out under the life cycle analysis-integrated waste-management project (LCA-IWM) supported by the European Union. The Waste Prognosis Tool helps to model

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and predict changes in waste generation based on actual tonnage data as well as (underlying) demographic and socio-economic developments occurring at the city level. For more details on the tool see Beigl et al. (2003) and Boer et al. (2005).

In general, most computer simulation applications using system dynamics models rely on the use of the software Vensim and Stella\textsuperscript{a}, both of which allow handling of the mechanisms of system dynamics with little complications. Other modeling systems which were also developed include those that are specialized for particular applications such as for business (e.g., Powersim). Stella\textsuperscript{a} is one of the first dynamic modeling systems to achieve broad recognition, due in large part to its user-friendly iconographic interface (Costanza and Voinov, 2001) to facilitate building of dynamic systems and have components that are intuitively assembled to simulate the dynamic processes. It also includes a procedural programming language which is useful for viewing or modifying the operations and variables created. The model also has the advantage that simulations can be run over different periods of time and provides the facility to conduct partial simulations to focus on specific sectors of a model (Hannon and Ruth, 2001; Deaton and Winebrake, 2000). The model developed here presents a system dynamic method developed using Stella\textsuperscript{a} to help in assessment of waste-management options that are often done by planners and decision makers. The utility of the model is demonstrated by fitting its framework to Newark, a representative city in New Jersey (NJ), USA, and by running a forecast simulation for a period of 10 years. The impact of decision options on the generation of waste in the city, on the remaining landfill capacity of the state, and on the economic cost or benefit actualized by the different waste processing options are explored through this approach.

2. Methodology

Real world phenomena are being increasingly conceptualized as systems that act and respond to the state of the components that they are made of, working interactively to form and act as a whole. Systems can be referred to as any collection of entities that includes four main components viz., reservoirs or reservoirs (state variables), processes or ongoing activity in the system that determines the contents of the reservoir (control or flow variables), converters which are system variables that often dictate the rates at which processes operate, and inter-relationships that represent the intricate connections among all components of a system (Deaton and Winebrake, 2000). Components of the system that are being modeled are conceptualized to interact with each other and are known as feedback processes. Feedback processes are known to occur if changes in a system component initiate changes in other components, which in turn affect the component that originally set off the change (Hannon and Ruth, 2001). Spreadsheets, process maps and optimizing models often can have detailed complexity including many elements, however, employing a sector-based piecemeal approach. The relative advantage of a system dynamic model is that they can include small to large parameter changes which may be incidental or continual and efficiently integrate the resultant complex feedback mechanisms. These may have many interconnections across various sectors of a process structure, making it easier to analyze and manage complex adaptive systems, such as the waste-management system, comprehensively, as compared to static systems. The response time of the system to a stimulus, termed as its time-lag, may be of varying nature too. Variation in feedback processes within a system can also be brought about by non-linear relationships. This often occurs when the flows or control variables do not depend on other variables in a linear fashion (Hannon and Ruth, 2001).

The four main components in Stella\textsuperscript{a}'s programming procedures that are used to build a systems scenario include stocks (state variables, represented by a rectangle); flows (processes: in and out of the state variable, valve with block arrow symbol), auxiliary variables (converter: algebraic and graphical relationships or fixed parameters, symbolized by a lone circle) and information flows (connectors or inter-relations, symbolized as simple arrows) (Fig. 1). In Stella\textsuperscript{a} model, equations are automatically generated and made accessible beneath the model layer. The system is geared mathematically towards formulating models as systems of ordinary differential equations and solving them numerically (Costanza and Voinov, 2001).

2.1. System dynamic modeling for municipal solid waste management

The dynamic system developed here incorporates the complexity of the waste generation and management process to some extent and the complexity in turn is achieved through a combination of simpler sub-processes that are linked together to form a whole. The process involves identifying the parameters that are determined to influence waste generation which are then added as inputs to the model and are interpolated for the intermediate years to allocate the city under consideration to a specific prosperity level. Based on the prosperity level, the appropriate regression equations derived through time-series and cross-sectional data analysis for the generation of total MSW is used to obtain the final generation results for the assessment year. Thus, the changing processes of city status are captured through time making the prognosis dynamic in nature.

This system-based prediction and response model considers recyclables, organic waste, and other discards including mixed and un-separated residual waste and seeks to extend the formulating concepts to assess further process consequences and thereby extend the utility for understanding and assessing the complex interactions. The estimations are based on analyses of the relationship between socio-economic and demographic conditions and the waste generation rate. While choosing the influencing parameters, constraints are introduced so as to focus on those that are the most easily available. The factors which were found to have a significant influence from research studies for the LCA_IWM prognosis tool on MSW generation thus included gross domestic product per capita, infant mortality rates, the population aged 15–59, house-hold size, life expectancy at birth and labor force in agriculture (Salhofer, 2001; Sirca, 2002; Lindh, 2003; Dennison, 1996; Rufford in Salhofer 2001 – as cited in Beigl et al., 2003). Further, to assess the standard of living and level of prosperity in a region which reflect a strong relationship to economic output and related process like waste generation and to make the selected variables comparable across regions, the following five indicators having overlap with the previously mentioned ones are selected, which include population density, gross domestic product (GDP), life expectancy at birth, infant mortality rate, and labor force (agriculture/services/
industry) (Mertins et al., 1999; Bogner et al., 1993 – as cited in Beigl et al., 2003). The basic model structure for city-scale waste generation is built based on the principles and relationships that were established in the tool LCA_IWM for waste prognosis (refer Beigl et al., 2003). The model development was carried out for Newark city, being one of the larger urban centers and being a region representing the urban flux expected in the state of New Jersey. Two independent estimations are carried out separately to include forecast of total waste generation and that of separately collected waste fraction for the period 2003–2013 which is chosen as the assessment horizon. The individual waste fractions modeled include paper and cardboard, metals, plastic, glass, hazardous waste and organic waste. The waste fraction collection data for the city was obtained from the municipal recycling tonnage records maintained at the Essex County Utilities Authority (ECUA, 2003), being the public body corporate for Newark city. The state variables in the model are total MSW generated per person in a given year, which is defined as a conveyor stock, the total MSW generated during the entire period, and the total amount of landfill space available with and without city level waste prevention measures. In order to facilitate simpler representation of the model operation, a simple schematic outline is presented in Fig. 2. Fig. 2 illustrates the flow diagram for the municipal solid waste-management system for total waste generation. Waste potential regression equations obtained through city-scale time-series data are used for the separately collected waste components to obtain the mass percentage value for the assessment year. As the calculation employed the system model's discrete object operations, along with built-in functions, Euler's method was used for the iterative runs, where the computed values for flows provide the estimate for the change in corresponding stocks over the time interval. For each iteration, a step size time variable (DT) of 1 year is used.

### 2.2. Landfill module

Increasing rate of disposal and the corresponding decrease in disposal capacity in landfills and rising public awareness of landfills and their environmental impacts have resulted in increasing the pressure on decision makers to seek alternate waste-management solutions. As a result of new federal regulations that were introduced such as the RCRA Sub-title D regulations for landfills in the US (USEPA, 1993), location and construction of new landfills has become increasingly difficult and more expensive. Landfill disposal which used to be the cheaper alternative is, thus, likely to become the less cost-advantageous option in the short-run for smaller states like New Jersey. The need to evaluate the remaining capacity of landfills available in a state is, thus, crucial. Keeping this need in mind, a landfill capacity estimation module was developed for the state, integrating system dynamics model feedback processes, building on the framework process that was advanced earlier for waste prognosis.

The major components of the flow in the landfill module are shown in Fig. 3. Sector 1 show the scenario of landfill capacity calculation for the state of NJ when no waste prevention measures have been established by authorities in the forecast period of 10 years. The NJ landfill sector receives information on the total amount of MSW generated per year from the average amount of MSW generated per year in 2003 as reported by the NJ Department of Environmental Protection's solid waste-management plan (NJDEP, 2006). The population estimate for the state in the assessment year is calculated from the interim projections available through the census database, with general assumption that recent state-specific trends in fertility, mortality, domestic migration, and international migration will continue for the state (US Census Bureau, 2008). The calculations for unit volume occupied by com-

![Fig. 2. Simple schematic diagram of total municipal solid waste generation systems model.](image-url)
Imacted waste that is disposed off in landfills considered the maximum compaction value of 75% (using heavy compaction equipment) which is generally achieved. For uncompacted density the standard value of 148.31 kg/m³ (250 lbs/yd³) (Robinson, 1986) is

Fig. 3. Stella flow diagram of the system dynamic model for total municipal solid waste management and landfill capacity estimation.
used. The US Environmental Protection Agency’s (USEPA) compaction estimate of 118.65 kg/m³ (200 lbs/yard³) for mixed waste is found to be less conservative for the purpose here (USEPA, 1994). The standard of using one part of soil cover to four parts of solid waste while landfilling was used in the estimation. The percent of in-state and city waste that is exported to other states in accordance to the existing interstate commerce law that is being practiced nationwide and diversion due to other waste processing options are further factored in while making the calculations. The rate of filling of the NJ landfill is calculated using the relation

\[ \text{Rate}_{\text{fill}} = P_{\text{Yr}} \times \text{CWV} \times \text{WD}_{\text{in-state}} \]

where \( \text{Rate}_{\text{fill}} \) = rate of landfilling in the assessment year (m³/year), \( P_{\text{Yr}} \) = population estimate for the assessment year, CWV = unit volume of compacted waste and soil in the landfill (m³), \( \text{WD}_{\text{in-state}} \) = proportion of waste diverted to in-state landfills.

The Newark landfill module on the other hand, in addition to the above source, also receives information feedback on the total MSW generated in the city, from the waste prognosis module developed and described earlier. The total percentage of local waste generated that is disposed of within the state of NJ in 2003 is found to be 20%, calculated from data available in the solid waste-management plan (NJDEP, 2006). The percentage diverted is assumed to continue for the period of model prognosis. The volume of landfill space remaining in NJ in 2003 is reported to be 31.9 × 10⁶ m³ (41.7 × 10⁶ yd³) (NJDEP, 2006). Regarding the waste that is imported by the state, it can be assumed that any waste that NJ imports is primarily for feed stocks for maintaining incinerator operations and little of it is used for landfilling. This module also provides information on MSW reduced by taking into consideration the possibility of introducing waste prevention measures, both intra-office and public ones in the city of Newark, which in turn is initiated by a decision process that is triggered by information on the total remaining landfill capacity in the state. This feedback process is facilitated by the decision diamond function available in Stella®. The decision criteria that is arbitrarily chosen here is if landfill disposal from the state in a particular year exceeds 10% of the remaining landfill capacity, then a decision process for waste reduction would be initiated by the policy makers. This value was chosen under the assumption that knowing the landfill capacity would expire in less than 10% of the total landfill life under current generation rate and management process, decision makers might initiate prevention measures to prolong the landfill life, before capping and closure. A percent target reduction rate of 50% is assumed to be set by the policy makers, as this was the target set for cities including Newark by ECUA officials in 2006 (ECUA, 2006).

The actual effect of the city-wide target policy measures on total MSW reduction is determined by waste prevention potentials that have been studied and reported in previous works (Beigl et al., 2004), and are used in this model (Table 1). The model sectors were run with a time step of 1 year. The resultant effect on reduction of wastes both from public and internal government sources and ultimately on the landfill capacity in terms of increase in cubic yards of disposal space is estimated using the relation:

\[ \text{MSW}_{\text{reduced}} = [(\text{Pub} + \text{Int}) \times \text{MSW}_{\text{Yr}} / D] \times P_{\text{Yr}} \]

where \( \text{MSW}_{\text{reduced}} \) = volume of MSW reduced in the assessment year (m³), \( \text{Pub} \) = waste reduction through public prevention measures (%), \( \text{Int} \) = waste reduction through intra-office prevention measures (%), \( \text{MSW}_{\text{Yr}} \) = MSW generated per person in the assessment year (kgs/cap/yr), \( D \) = density of compacted waste at landfill (kgs/m³), \( P_{\text{Yr}} \) = population estimate for the assessment year.

A higher value in general, indicates a higher rate of effectiveness of waste prevention measures. The module is thus expected to provide a more realistic scenario of the future impact of waste management on landfill capacity change in the presence and absence of prevention measures initiated by policy makers.

2.3. Separate collection sector

Solid waste composition analysis of future waste generation is an important factor for determining resource recovery plant capacities and for establishing alternative management procedures that facilitate increased recycling practices. In addition to factoring in the influence of demographic and socio-economic influence, the waste potentials data of particular fractions in the waste stream as well as their tonnages in both separately collected and residual components are used for defining the systems model here. A time frame of 10 years (2003–2013) was chosen as the forecast period, being a typical time frame for return of investments on policy implementations. Using coefficient models to describe functional relationships between the parameters used, as was carried out for the prognosis model, the systems sector developed here helps to estimate future waste generation of individual fractions for the city of interest. The simulated change in the MSW components with time are further subject to analysis dependent on possible relationship changes with other economic driving factors. The residual waste mass percentage of each fraction is calculated to more accurately assess the component proportion in the final bulk. In the later stages, the systems model also provides the tonnage of the individual uncollected waste fraction that were disposed of without recycling, giving an estimate of each component that is ‘truly wasted’ each year.

2.4. The cost of policy options

In addition to the above assessment of uncollected waste components, the consequences of status quo management methods and policies are also explored in the separately collected waste sector. As the estimate of future solid waste quantities must also take into account actual or likely development of resource recovery facilities, and the impact on waste generation that recycling may have on future refuse quantities (Robinson, 1986) disposal cost versus recycling cost dynamics that are likely to occur in the future are also considered for this systems analysis. Regions that exhaust their landfills space would be forced to find sites elsewhere often farther away or use alternate disposal methods, both of which potentially increases the marginal cost of management. The impact of landfill capacity usage is thus considered to affect the future disposal costs of waste fractions. A disposal cost decision process function was used to translate this effect to the final cost difference on recycling versus landfilling expenditure, in order to see the possible time frame when either of the practices would be profitable. This can be further conceptualized with the relation

\[ \Gamma_i = C_{\text{Ri}} - B_{\text{Ri}} - C_{\text{Li}} \]

where \( \Gamma_i \) = cost of new landfill space (landfill space scarcity) at time i, \( C_{\text{Ri}} \) = costs of recycling, \( B_{\text{Ri}} \) = benefits of recycling, \( C_{\text{Li}} \) = costs of landfilling (Huhtala, 1997).

There is high probability that the cost of recycling would fall in the future due to increased public participation (DSM, 2008), and the price of recyclables beginning to rise in many parts of the country (Wollan, 2008) as the economic infrastructure of the recycling industry begins to expand and solidify its operations. Accordant to the above relation, an appropriate transition curve was defined, and consideration was given to reduce the chances of predicting a short-time frame for the average difference between the two management options to change signs. The curve was further defined by considering the other alternative methods of waste processing such as incineration and extension of waste export processes which would help to avoid the scenario where recycling would
be 100% more beneficial in terms of expenditure, than landfilling. The same reasoning is used to avoid allocating the absolute negative proportion value of \((-1)\) to the impact factor of the disposal cost decision function (with limits \(-1\) to +1), when recycling becomes more profitable than landfill disposal. Fig. 4 shows the ratio of landfill space, and the corresponding impact factor that was defined by extending a curve of influence, where the price difference decreases slowly in the beginning and then begins to accelerate towards the later years due to increasing pressures to use alternate measures of waste processing. The sloping curve intends to capture the general behavior of public commodity price decisions as supply diminishes. The turning point where the cost of landfilling supersedes cost of recycling is set where the ratio of remaining landfill is less than 20%. This value was chosen as currently a portion of the waste generated in the state (20%) is landfilled within the state, which is based on the diversion rate determined by the equilibrium market price. If less than 1/5th of in-state landfill space remains, it is assumed that it would make an increase in exports of waste from the state necessary in a relatively short period, moving the equilibrium market price upward, thereby increasing the costs of landfilling. As the landfill capacity ratio approaches this value, any additional generation would be processed more cost effectively and in a more socially acceptable manner by recycling, rather than by landfilling either within state or by exporting out of state. The desired choice of increasing recycling rate versus disposal at landfill, however, will be based on its net unit cost relative to the other. The city being in the Greater New York area, the disposal cost of total MSW and recycling costs of four main components (paper, metals, glass, and plastics) in addition to their recycling revenues, reported by DSM environmental for New York city in 2005 conducted in collaboration with the Department of Sanitation, NY and Natural Resource Defense Council (DSM, 2008) were used here to determine the overall cost burden of each alternative.

Further in order to investigate whether city-scale waste prevention measures that were introduced as a response to dwindling landfill capacity have the potential to affect the cost of either landfilling or recycling processes or both in the future, an additional extension to the system was defined involving comparative assessment of the decision process integrated with the balance of expenditure associated with the waste processing options.

### 3. Results and discussion

The model parameters and initial values of all state variables were determined for the model calibration process. The parameters include initial (reference year) amount and composition of the MSW generated obtained from county records (ECUA, 2003). Table 1 and Fig. 4 illustrate the impact of landfill capacity ratio to disposal versus recycling cost.

**Table 1**

<table>
<thead>
<tr>
<th>Waste prevention measures at municipal level</th>
<th>Prevention potentials by fraction (mass %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paper and cardboard potential</td>
<td>Organic waste potential</td>
</tr>
<tr>
<td>Public measures</td>
<td></td>
</tr>
<tr>
<td>Mailbox sticker “no junk mail”</td>
<td></td>
</tr>
<tr>
<td>Promotion of repair services (guide)</td>
<td></td>
</tr>
<tr>
<td>Promotion of reusable goods (guide)</td>
<td></td>
</tr>
<tr>
<td>Promotion of hire services</td>
<td></td>
</tr>
<tr>
<td>Promotion of nappy services (subsidies)</td>
<td></td>
</tr>
<tr>
<td>Intensified municipal public relations</td>
<td></td>
</tr>
<tr>
<td>Promotion of the do-it-yourself composting</td>
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</tr>
<tr>
<td>Internal measures</td>
<td></td>
</tr>
<tr>
<td>Procurement of reusable material</td>
<td></td>
</tr>
<tr>
<td>Double-sided use of paper</td>
<td></td>
</tr>
<tr>
<td>Application of reusable towels</td>
<td></td>
</tr>
</tbody>
</table>

Source: (Beigl et al., 2004).

and influencing socio-economic indicator values obtained from public sector resources including NJDEP solid waste-management plan (NJDEP, 2006) for statewide waste generation and landfill capacity data, US Census Bureau (2007) for population and household size data, Bureau of Labor Statistics (USDOL, 2006) for GDP and labor force data, NJ Department of Health and Human Services (NJDHHS, 2008) and National Center for Health Statistics (2006) for life expectancy and infant mortality data. Data related to city or state wide waste generation and composition, both primary and secondary are usually hard to obtain due to the issues related to direct access and insufficient record keeping. Nevertheless, the county officials of Essex have been efficient in maintaining a good database for waste collected and recycled since 1996 for its various cities. All model development and validation processes, thus, had to be confined within this range. City scale and national level socio-economic and health data are also used for parameter values, which however may not be available for all cities for all years. In such situations, it becomes necessary to carry out statistical estimations for the required year. The model run results for the generation of total MSW and that of the separately collected waste fraction were subject to preliminary tests for validation using ex-post forecast analysis using the actual values available for 1996 and 2001. The input data including the waste fraction, socio-economic and demographic data and related trend values were collected for the respective years and entered as inputs and the model was executed. The steady collection rate results obtained were compared to the actual values of the assessment year and the error percentage for each waste fraction was computed. The model error percentage computed for the total MSW generated in the city yielded a value of 19.69%. The model was subject to sensitivity analysis by changing the variable values for total MSW initially generated at city scales which is the first input stock of the model. A comparative table with final output stock being the landfill capacity with city-scale waste prevention measures was then defined. Three cases were defined for the sensitivity test run by assigning two extreme values (i.e., minimum and maximum scenarios), keeping the current value as the median. The results obtained (Table 2) were proportional to the input variables defined and demonstrated the robustness of the model. The simulated results for the MSW generation and landfill capacity estimation for Newark city is presented in Table 3.

In the span of 10 years the total MSW generation is seen to increase from 1.94 tons/cap to 2.15 tons/cap showing a growth of 9.6%. With a steady increase in the prosperity factor coupled with population growth, the corresponding increase seen in MSW is as expected. Based on the permitted landfill capacity remaining in NJ, a sub-module was also developed which calculates the remaining amount of landfill space available to the state, both under business as usual scenario and under a decision process criteria, if the city of Newark implements a waste prevention measure with specific targets of reduction. The average rate of in-state landfill utilization per year (landfill rate of filling) provided by the model run results, shows an increase which is primarily attributed to population increase estimated for the state.

The decision criteria for waste prevention policy measures is seen to be initiated from the second year of generation as the landfilled waste volume the previous year exceeded 10% of the remaining capacity (Table 3). The effect of implementing a city-wide waste prevention measure with target rate of 50% is shown in Table 3 (column: landfill capacity in NJ with Newark waste prevention measures). The actual impact of the target percentage on total MSW reduction established in previous studies (Beigl et al., 2004) were factored in, to carry out the assessment. The resulting compacted volume of MSW saved from being landfilled is also provided by the model run for each year. The results show that the existing permitted land fill capacity in the state would be completely utilized within a span of 9 years (2012) and is far below the expected long-term life of typical landfills. Though implementing waste prevention policy measures in Newark city did not result in any significant increase in the period of landfill life in NJ, the difference in volume available for disposal each year is clearly seen in the results obtained. The volume made available for disposal continues to increase with the years from 30,783 m$^3$ to 34,077 m$^3$, which is associated with the rate of waste generation in the city, and is actualized by the waste avoided at source or diverted for recycling from the city. The total landfill volume of the state estimated to be saved during the period as a result of the city's waste prevention policy is 291,387 m$^3$. This estimate of waste generation and landfill space available as a result of implementing waste prevention policy measures is considered to be crucial for future planning of collection and processing facilities both at city and state levels of management.

The simulated results for the separate collection sector for the years up to 2013 for the city of Newark are shown in the following two tables. Table 4 shows the representative estimated values of all the waste fractions considered. In addition to providing the tons of the particular waste fraction that is likely to be generated in the assessment year, the table also provides the tonnage of the fraction that is disposed of in landfills. The tonnage continues to increase with increasing population and changing socio-economic conditions, as expected. Table 5 provides the estimates on the change in disposal costs associated with the change in landfill space regulated by the rate of impact decision factor and that of the balance of expenditure if the uncollected wastes were diverted for recycling at the end of each year rather than being landfilled.

As shown in Table 5 the values for landfilling and recycling costs continues to increase with the advance of years, primarily as a result of the upward changes in demographic and socio-economic conditions and corresponding increase in waste generation. The balance of expenditure columns reflect the difference in the total cost of recycling in relation to landfilling in millions of dollars per year for the uncollected portion of paper, metals, plastic and glass. In line with the assumptions propounded earlier, it can be seen that the economic benefit of recycling is lower (represented by negative values in terms of dollars) for the first 7 years starting with a differential cost of 1.43 million, compared to that of landfilling, due to the relatively lower cost of the latter. However, the cost advantage for landfilling continues to decline as a result of diminishing volume of landfill space available. In the 8th year (yr. 2011), the process of choosing recycling for the uncollected waste fractions as opposed to landfilling (in or out-of-state) becomes more cost effective, making it, in comparison, the preferred waste processing option in a business as usual scenario. As the in-state landfill capacity is completely utilized by the end of the 9th year (Table

<table>
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<th>#2</th>
<th>#3</th>
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<td>Years</td>
<td>Landfill capacity in NJ (m$^3$)</td>
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<td>46,744,823</td>
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<td>46,744,823</td>
<td>46,744,823</td>
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<td>36,681,720</td>
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* Per capita MSW generated in the first year.
the impression that recycling is not an economically advantageous process may in fact prove recycling to be more cost-efficient than landfilling in the shorter-run.

The model run results also reveal a previously overlooked pattern, where implementing a waste prevention measure in a city (in addition to factoring in the cost of implementing such a program) ultimately affects the profit margin between recycling and landfilling. Table 5 shows the values (balance of expenditure) for the cost of landfilling versus recycling for the two cases when a waste prevention measure is initiated in the city of Newark and when it is not. The impact caused by the difference in waste processing choices of a city though not large, is but noticeable. From the table we can see that, essentially, the margin of benefit of choosing recycling over landfilling is reduced as a result of implementing a waste prevention policy measure at city scales with a target rate of 50%. This trend in decrease of benefit continues even after recycling turns out to be more cost advantageous than landfilling. The reason for this is, as a result of increased waste prevention measures, more landfill space is made available each year after recycling, when it is not. The impact caused by the difference in waste processing choices of a city though not large, is but noticeable. From the table we can see that, essentially, the margin of benefit of choosing recycling over landfilling is reduced as a result of implementing a waste prevention policy measure at city scales with a target rate of 50%. This trend in decrease of benefit continues even after recycling turns out to be more cost advantageous than landfilling. The reason for this is, as a result of increased waste prevention measures, more landfill space is made available each year after the measures were implemented, in relation to when such measures were not implemented (Table 3), thereby prolonging the economic benefit of the lower cost of landfilling versus that of recycling. It is only in the final year when the landfill capacity has been completely utilized that the benefit difference becomes negligible. The systems model thus helps to bring out the fact that economic benefit of switching to recycling of uncollected waste in ever, this assumption is not true as the primary reason for the higher per ton recycling costs compared to landfilling cost seen at present is because that recycling collection crews collect far fewer tons per shift than refuse collection crews (DSM, 2008). Therefore policy measures that would promote efficiency in recycling processes may in fact prove recycling to be more cost-efficient than landfilling in the shorter-run.

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a state is sensitive to and inversely related to the implementing of local city-scale waste prevention measures. The sensitivity of the mean effect of waste prevention policies on the cost of the total waste processing options is expected to be especially relevant for future planning and analysis for waste-management decisions.

4. Conclusions

This research demonstrates that system dynamic modeling can provide a more comprehensive and sophisticated simulation method for integrated assessment of complex waste-management processes. The results showed that the generation of MSW undergoes a general increase during the period of forecast, due to the increase in the dimensions of the influencing socio-economic and population variables. The existing permitted landfill capacity is shown to be completely utilized in a span of nine years (by 2012). Implementation of a city-scale waste prevention measures initiated by a decision criteria based on remaining landfill space provides results for corresponding impact on in-state landfill space and on volume reduced which is reflective of the target percent set by the decision makers, its actual impact, the percent directed to the fills, and the per year waste generation character of the region. The separate collection sector analysis in addition to furnishing future waste component generation values also provided values of uncollected waste fraction tonnages for each year showing an increasing trend in line with the change observed in the causal variables. Similarly, waste processing cost were shown to follow an increasing trend, and the cost of landfilling, in response to the decrease in landfill space is shown to overtake that of recycling within 8 years, making recycling the preferred option for the uncollected wastes, though policies directed at improving operation efficiencies might shorten this period of transition. Investigation to the influence of implementing city-scale prevention policy measures on the waste processing options, contrary to common assumptions, revealed an adverse influence on cost for the recycling option due to the measure's positive impact on increasing landfill capacity. This would mean that allocating funds for waste prevention measures at city scales though would be helpful to extend the lifespan of in-state landfills, would however be at the cost of decreasing the percentage of recycling, and would be so until the transition of waste processing from landfilling to other means of disposal is complete. In light of the environmental impact that is propagated as a result, new policy measures that reduce the cost of recycling by increasing operation efficiencies and increase the markets for recyclables is recommended. This model is developed for testing and with adequate and relevant data will find important applications in real decision making for future target years. By utilizing real and plausible data from sources that are easily available and using statistical estimations of past behavior, the systems model developed here presents a more practical and realistic picture of the next decade in solid waste-management scenario for cities like Newark, NJ than is possible by more traditional approaches. The landfill capacity estimation module can be easily adopted for estimations for other states. Further, the model can also find applications in cases involving generic needs determination for siting new landfills in other regions of the country, and in determining the future potential economic impact of recycling or resource recovery activities, being especially useful for local and state decision makers. Further development of the model is warranted for the solution of more complex problems requiring more refined results for waste generation, siting capacity, choice of processing technology, collection and sorting efficiency, waste prevention particulars and associated budget allocations. This work concentrated primarily on the general economic impacts, and certain limitations remain in the lack of other associated economic, environmental and social impact modeling. This attempt, being an initial inquiry into the possibility of the systems analysis method to solve complex waste-management problems and reduce future uncertainty, there remains a tremendous scope to extend and further its utility by introducing new sub-component ranges and by allowing various natural and anthropogenic system components to be coalesced, thereby facilitating the system actors across boundaries to come together for developing integrated solutions.

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