The Application of Life-Cycle Assessment to Solid Waste Management: Applications, Challenges and Modeling Techniques

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The Application of Life-Cycle Assessment to Solid Waste Management: Applications, Challenges and Modeling Techniques

James W. Levis
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Introduction and Objectives

- Perspective on accomplishments to date
  - Observations on tools
  - Range of applications to illustrate methods
  - Methodologies
    - Uncertainties
    - Tradeoffs
  - Challenges
- Somewhat focused on U.S and very focused on waste
  - hope will stimulate dialog
- Municipal solid waste (MSW)
  - Residential, multifamily, commercial
  - Not industrial, biosolids
Introduction and Objectives

- The application of life-cycle assessment to solid waste management has been discussed for about 25 years
  - Integrated Solid Waste Management: A Life-Cycle Inventory (McDougall, White, Franke and Hindle, 1994)
The Solid Waste System is Complex

The Solid Waste System

- The beneficial use of products is included
  - Energy from anaerobic digestion, landfill, combustion
  - Land application of compost
  - Offsets from recyclable materials
The Solid Waste System and Study Objectives

- Defining the study objective is essential and the system definition may vary
  - We understand the solid waste system very well
  - We can help with product LCAs with rigorous evaluations of the waste management component
  - We need to do a better job of integrating our expertise with others working on product and process LCAs
Functional Units

- 1000 kg (1 Mg) of MSW at the curb
  - Neglects what happens in the house, backyard composting
  - Focus on what the local solid waste authority can influence which is useful for decision support at the local level
  - May be different for a policy analysis at the national level

- 1000 kg disposed in a landfill at time zero
- 1000 kg in a landfill regardless of time (the landfill is then the functional unit)
- The best way to deliver 500 mL of beer
- Waste elimination or “source reduction”
Observations: Simplicity vs Complexity

- What is the intended use? Who is the intended user?
  - Education
  - An LCA course
  - Policy research and local decision making
    - Engineering practice - still a screening tool
- Technology optimization/improvement assessment
- Challenging tradeoffs between simplicity and complexity (model flexibility) that must be considered in model design
  - Municipal solid waste vs ~30 waste components
  - Choices for the equipment configuration at a sorting plant vs. one option
  - Choices in impact factors and weighting schemes
  - Flexible energy grids
Advanced Models

- **Solid waste management life-cycle optimization framework (SWOLF)**
  - Allows user to explore alternate strategies in consideration of constraints
  - Multi-stage optimization model
    - Waste composition and energy grid are dynamic – allowed to change in 5 year intervals
  - Maximally flexible
  - Use in optimization or accounting mode

- **EASETECH**
  - Comprehensive model of the solid waste system; incorporates additional waste types and processes
  - Accounting mode only, superior interface
  - Uncertainty assessment
**WARM Inputs (U.S. EPA) (GHG Only)**

### Steps 1 and 2: Baseline and Alternative Scenarios

<table>
<thead>
<tr>
<th>Material</th>
<th>Baseline Scenario</th>
<th>Alternative Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tons Recycled</td>
<td>Tons Source Reduced</td>
</tr>
<tr>
<td></td>
<td>Tons Landfilled</td>
<td>Tons Composted</td>
</tr>
<tr>
<td></td>
<td>Tons Combusted</td>
<td>Tons Recycled</td>
</tr>
<tr>
<td></td>
<td>Tons Landfilled</td>
<td>Tons Composted</td>
</tr>
<tr>
<td></td>
<td>Tons Combusted</td>
<td>Tons Recycled</td>
</tr>
<tr>
<td></td>
<td>Tons Landfilled</td>
<td>Tons Composted</td>
</tr>
<tr>
<td>Aluminum Cans</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminum Ingot</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steel Cans</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Copper Wire</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glass</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HDPE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LDPE</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>PET</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LLDPE</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>PP</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>PS</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>PVC</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>PLA</td>
<td>N/A</td>
<td></td>
</tr>
</tbody>
</table>

### Step 3: Landfill Characteristics

- National Average
- No LFG Recovery
- LFG Recovery
  - Recover for energy
  - Flare

### Step 4: Waste Transport Characteristics

- Use default distance
- Define distance

### Step 5: Results Output

- Metric Tons of Carbon Dioxide Equivalent (MTCO2E)
- Metric Tons of Carbon Equivalent (MTCE)
- Units of Energy (million BTU)

<table>
<thead>
<tr>
<th>Management Option</th>
<th>Distance (miles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landfill</td>
<td>20</td>
</tr>
<tr>
<td>Combustion</td>
<td>20</td>
</tr>
<tr>
<td>Recycling</td>
<td>20</td>
</tr>
<tr>
<td>Composting</td>
<td>20</td>
</tr>
</tbody>
</table>

User maintains mass balance

https://www3.epa.gov/warm/Warm_Form.html
SWOLF-EDU: used in undergraduate environmental science class

Introduces students to LCA, tradeoffs, systems thinking
Includes costs, forces mass balance; some flexibility

<table>
<thead>
<tr>
<th>Materials</th>
<th>Generated Composition (%)</th>
<th>Generated Mass (Mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Food Waste</td>
<td>12.0</td>
<td>120</td>
</tr>
<tr>
<td>Yard Waste</td>
<td>12.0</td>
<td>120</td>
</tr>
<tr>
<td>Recyclable paper</td>
<td>12.0</td>
<td>120</td>
</tr>
<tr>
<td>Cardboard</td>
<td>12.0</td>
<td>120</td>
</tr>
<tr>
<td>Other Compostable Fiber</td>
<td>5.0</td>
<td>50</td>
</tr>
<tr>
<td>Other Paper</td>
<td>5.0</td>
<td>50</td>
</tr>
<tr>
<td>PET Bottles</td>
<td>5.0</td>
<td>50</td>
</tr>
<tr>
<td>HDPE Containers</td>
<td>5.0</td>
<td>50</td>
</tr>
<tr>
<td>Plastic Film</td>
<td>3.0</td>
<td>30</td>
</tr>
<tr>
<td>Other Plastic</td>
<td>3.0</td>
<td>30</td>
</tr>
<tr>
<td>Aluminum Cans</td>
<td>2.0</td>
<td>20</td>
</tr>
<tr>
<td>Steel Cans</td>
<td>2.0</td>
<td>20</td>
</tr>
<tr>
<td>Other metals</td>
<td>3.0</td>
<td>30</td>
</tr>
<tr>
<td>Glass Bottles</td>
<td>2.0</td>
<td>20</td>
</tr>
<tr>
<td>Other Glass</td>
<td>2.0</td>
<td>20</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>15.0</td>
<td>150</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>100</strong></td>
<td><strong>1,000</strong></td>
</tr>
</tbody>
</table>
SWOLF

go.ncsu.edu/swolf
Use optimization modeling to evaluate multiple alternatives for solid waste management for State of Delaware
- Consider cost, emissions, energy consumption
- Consider scenarios that may differ from current practice

Work conducted using the Municipal Solid Waste Decision Support tool (MSW-DST) (first generation tool)
Modeling Solid Waste Management in Delaware: A Statewide Analysis

- **Challenge**: 3 counties and the funding authority does not control waste collection
- **New Castle County**
  - Urban
  - 64% of the state population
- **Kent County**
  - Suburban to rural
  - 16% of the state population
- **Sussex County**
  - Suburban to rural
  - 20% of the state population
How Do we Combine Counties to Provide the State a Meaningful Roadmap?

The manner in which waste is handled is similar …
How Do we Combine Counties to Provide the State a Meaningful Roadmap?

... but collection costs per Mg are higher in the rural counties
Variation of Waste Flows, Cost, & GHE with Diversion
[curbside recycling + yard waste composting + combustion]

- In Sussex County, a mixed waste MRF is utilized upstream of combustion to reduce transport costs
- Composting and curbside recycling only used near maximum diversion with resultant increases in GHE emissions
- Larger GHG decreases possible in New Castle County (more populated)
Using an Optimization Approach: Observations from County-Wide Summary

- Non-uniform utilization of curbside collection, combustion subject to a cost constraint
- Optimization model led to counter-intuitive results
  - MRF upstream of combustion
  - Effectiveness of recycling and yard waste composting influenced by transport distance
### Identify the Cost-effective 30% Statewide Diversion Strategy?

<table>
<thead>
<tr>
<th>DIVERSION</th>
<th>Cost [$/yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>New Castle</td>
</tr>
<tr>
<td>30%</td>
<td>42,050,377</td>
</tr>
<tr>
<td>30%</td>
<td>42,050,377</td>
</tr>
<tr>
<td>30%</td>
<td>42,050,377</td>
</tr>
<tr>
<td>30%</td>
<td>42,050,377</td>
</tr>
<tr>
<td>30%</td>
<td>42,050,377</td>
</tr>
<tr>
<td>35%</td>
<td>43,245,513</td>
</tr>
<tr>
<td>35%</td>
<td>43,245,513</td>
</tr>
<tr>
<td>35%</td>
<td>43,245,513</td>
</tr>
<tr>
<td>35%</td>
<td>43,245,513</td>
</tr>
<tr>
<td>35%</td>
<td>43,245,513</td>
</tr>
</tbody>
</table>

- **Uniform diversion is not least cost case**

- **Least-Cost 30% Statewide Diversion**

- The optimal statewide strategy is a combination of three unique SWM alternatives that are county-specific
  - a uniform statewide strategy will be sub-optimal
Generating Alternative SWM Strategies

- Optimal solution may not be appropriate
  - political feasibility
  - capital intensive
  - facility siting
  - Combustion prohibited

- Generate alternatives that maximize differences in unit operations & waste flow choices in SWM strategies using Modeling to Generate Alternatives (MGA)
Cost-effective 30% statewide diversion strategy includes:

- **cost-effective 35% diversion from New Castle**
  
  Cost: $43.2 M/yr \rightarrow \text{relax the cost} \rightarrow $48 M/yr

- **cost-effective 20% diversion from Kent**
  
  Cost: $20.2 M/yr \rightarrow \text{relax the cost} \rightarrow $22.5 M/yr

- **cost-effective 20% diversion from Sussex**
  
  Cost: $34.6 M/yr \rightarrow \text{relax the cost} \rightarrow $38.7 M/yr
## Waste Flows for Alternative SWM Strategies to Achieve 30% Statewide Diversion

<table>
<thead>
<tr>
<th></th>
<th>Least-Cost</th>
<th>NC-Alt 1 + K-Alt 2 + S-LC</th>
<th>NC-Alt 2 + K-Alt 2 + S-Alt2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mixed Waste Transfer</strong></td>
<td>tons/yr</td>
<td>24394</td>
<td>19894</td>
</tr>
<tr>
<td><strong>Pre-Sorted Transfer</strong></td>
<td>tons/yr</td>
<td>719</td>
<td>7185</td>
</tr>
<tr>
<td><strong>Mixed Waste MRF</strong></td>
<td>tons/yr</td>
<td>73554</td>
<td>83665</td>
</tr>
<tr>
<td><strong>Presorted MRF</strong></td>
<td>tons/yr</td>
<td>86696</td>
<td>32717</td>
</tr>
<tr>
<td><strong>Commingled MRF</strong></td>
<td>tons/yr</td>
<td>0</td>
<td>7431</td>
</tr>
<tr>
<td><strong>Yard Waste Composting</strong></td>
<td>tons/yr</td>
<td>0</td>
<td>13115</td>
</tr>
<tr>
<td><strong>Combustion</strong></td>
<td>tons/yr</td>
<td>80564</td>
<td>118017</td>
</tr>
<tr>
<td><strong>Diversion</strong></td>
<td>%</td>
<td>30</td>
<td>30</td>
</tr>
</tbody>
</table>
Case Study for Wake County, North Carolina, USA

- 12 independent cities with their own collection systems
  - Each city contracts with county for some solid waste services, primarily the landfill
  - The cities control residential but not commercial waste
    - Commercial waste must be considered for capital investments
  - Substantial data development
Waste Generation Sectors

- **Single-family (SF) residential waste generators**
  - Waste generation, composition, and collection details specified for each municipality (12)

- **Multi-family (MF) residential waste generators**
  - Waste generation, composition, and collection details specified for 2 MF sectors: 1) Raleigh 2) other cities

- **Convenience centers (CC)**
  - Generation at city and county sites combined

- **Commercial waste generators (COM)**
  - Only includes residual waste – excludes any source-separated recyclables or food waste
  - Residual waste split between 2 landfills
Next Steps

- We have represented the current system and have reasonable agreement to mass flows and costs with actual data
- Consider population growth and changes in waste composition over a 30 year time horizon
- Develop optimal scenarios for each city and combine
Consumer Packaging Study: Is biodegradability a desirable attribute for discarded solid waste?

- Interest in the environmental footprint of consumer products
  - Many disposed in landfills
  - U.S. and globally
  - Work to represent the national average landfill
    - Weighted average of landfills that
      1. Collect gas and use beneficially
      2. Collect gas and flare
      3. Do not collect gas
Material modeling in landfills

- National Average landfill
  - GHG Emissions (MTCO₂E/Mg)
  - Categories: Generated Methane, Collected Methane, Oxidized Methane, Stored Carbon, Energy Offset, Total
  - Colors: MSW (green), Food waste (light blue), Newsprint (yellow), Office paper (purple), PHBO (brown)

- State-of-the-art landfill
  - GHG Emissions (MTCO₂E/Mg)
  - Categories: Generated Methane, Collected Methane, Oxidized Methane, Stored Carbon, Energy Offset, Total
  - Colors: MSW (green), Food waste (light blue), Newsprint (yellow), Office paper (purple), PHBO (brown)
Observations

- Slower biodegradation is better (national average)
- Recalcitrant biogenic carbon is optimal based on disposal
  - Must now integrate this with the production process

Observations

- Consider a developing country and disposal of a specific material in an uncontrolled landfill (open dump)
  - allocation methodology now becomes critical
  - plastic packaging may not leach or biodegrade
    - Residual contents will
## Uncertainty in Solid Waste LCA

<table>
<thead>
<tr>
<th>Process</th>
<th>Model Uncertainty</th>
<th>Scenario Uncertainty</th>
<th>Parameter Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>General</td>
<td>Linearity</td>
<td>System boundaries, Spatial and temporal variation, Allocation</td>
<td></td>
</tr>
<tr>
<td>Impact Assessment</td>
<td>Modeling fate and effects</td>
<td>Normalization and weighting methods</td>
<td>Characterization factors</td>
</tr>
<tr>
<td>Composition</td>
<td></td>
<td>Choice of composition</td>
<td>Waste fraction distribution, material properties</td>
</tr>
<tr>
<td>Collection</td>
<td>Collection model</td>
<td>Choice of collection scheme</td>
<td>Fuel efficiency, emission factors</td>
</tr>
<tr>
<td>Treatment</td>
<td>Process models and sub-process models (e.g., landfill gas)</td>
<td>Choice of technology (e.g., state-of-the art vs. average)</td>
<td>Emission factors</td>
</tr>
<tr>
<td>Beneficial recovery</td>
<td>Process model</td>
<td>Choice of offsets and technologies</td>
<td>Substitution rate, emission factors</td>
</tr>
<tr>
<td>Energy System</td>
<td></td>
<td>Choice of marginal fuel(s)</td>
<td>Emission factors, fuel efficiency</td>
</tr>
</tbody>
</table>

Intrinsic LCA Modeling Uncertainties

- Lack of spatial/temporal information on environmental impacts
- Assumption of linearity
- Characterization factor choices and uncertainties
  - Can be related to spatial/temporal uncertainty
  - GWP for methane is 72, 25, or 7.6 kg CO$_2$e/kg CH$_4$ using 20, 100, or 500 year horizons (static case)
Tools to evaluate uncertainty and sensitivity

- **Scenario analysis**
  - What significant parts of the analysis are likely to differ from what was modeled?

- **Contribution analysis**
  - What processes, materials or emission have the largest effect on results?

- **Parametric perturbation analysis**
  - How do results change if you change parameter values?

- **Uncertainty propagation**
  - What is the actual distribution of result values and how are they correlated with parameter uncertainty?
Scenario Analysis

- Useful for modeling alternative possibilities
  - Use different allocation method(s)
  - Use different offset(s)
  - Use different fuel/electricity sources
- Provide a broad look at how changes to the system affect results
- Provides information on the robustness of the results
Effect of composition

- Developed per capita generation trends for 30 waste materials based on EPA 2012 MSW Facts and Figures data.


The WTE facility is used only in the first stage because there is more paper and less plastic than in the following stages and because of the decrease in electricity GHG intensity.

AD use over time increases as more food waste is generated.

Electricity GHG Intensity

Food Waste Management Example

Natural Gas (0.74 kg CO₂e/kWh)  
Coal (1.3 kg CO₂e/kWh)

Base case used 55/45 Coal/Natural Gas split based on marginal split in the Southeastern Electricity Reliability Council (SERC) grid (0.89 kg CO₂e/kWh)

Contribution Analysis

- Compare the contributions of the various sub-processes and/or materials involved in your process or product to various impacts.
Parameter Perturbation Analysis

Landfill Global Warming Potential

GWP (kg CO$_2$e)

0 10 20 30 40 50 60 70 80 90 100
Percent of Interval Range

-400 -350 -300 -250 -200 -150 -100 -50 0

Moisture Content  Methane Yield  Decay Rate  Carbon Storage Factor  %Coal Offset
Methodology for Uncertainty Propagation: Monte Carlo Analysis

- Probability Distributions for Uncertain Parameters
- Latin Hypercube Sampling
- A Set of Input Values
- A Set of Cost & LCI Coefficients
- Solve Unit Process Models
- A Realization
Methodology for Uncertainty Propagation

SWM Strategy: Unit Processes & Mass Flow

- Probability Distributions for Uncertain Parameters
- Latin Hypercube Sampling
- A Set of Input Values
- A Set of Cost & LCI Coefficients
- Solve Unit Process Models
- A Realization

Cost and LCI Coefficients

Simulation

Cost and LCI Estimates
Probability Distributions for Uncertain Parameters

A Set of Cost & LCI Coefficients

Solve Unit Process Models

A Set of Input Values

Latin Hypercube Sampling

A Realization

Methodology for Uncertainty Propagation

SWM Strategy: Unit Processes & Mass Flow

Cost and LCI Coefficients

Simulation

Multiple Realizations

Output CDF & Correlation Coefficients

Cost and LCI Estimates
Example Result: Monte Carlo Analysis

32% chance of exceeding the deterministic value of 33 million

Expected: 32
Range: 27.6-37.0
Monte Carlo Analysis

Landfill GHG Emissions


Food waste composting NOx emissions


Are differences between scenarios robust?

Time Dependent impact of GHGs

- The effect a GHG emission has on radiative forcing varies with time and with existing atmospheric concentrations of GHGs (which also vary with time).
- Dynamic GWIs reduce the impact of future emissions based on the change in radiative forcing of those future emissions.
  - Requires dynamic LCIs
  - May include explicit discounting


Material Reprocessing Offsets: Important but …

... Uncertain

- Energy grid is critical, not always separable
- Country of material processing may not be the country of use

Laurent et al. (2012) found climate change was generally a reasonable proxy for impacts primarily affected by fossil energy use (e.g., acidification, photochemical oxidation) and potentially poor proxy for toxicity and non-fossil resource use impacts.

Steinmann et al. (2016) found that marine ecotoxicity and climate change indicators covered 84% of the variance in life-cycle product rankings.

- The addition of land use and ozone depletion accounted for 90.1%
Conclusions and Challenges

- Every study is different and will require different applications of available models
- The optimal system may require coordination between several cities or cities and commercial companies
  - This may not be possible
- How do we express results simplistically so that non-LCA experts can use?
  - Expressing uncertainty is critical to our collective credibility
- As LCA and waste experts, we are best prepared to analyze and interpret
- Do not forget that no one steals garbage, but some people will steal sorted aluminum cans
Acknowledgements

- Ranji Ranjithan, Joe DeCarolis
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