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A generalized multistage optimization modeling framework for life cycle assessment-based integrated solid waste management

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A B S T R A C T

Solid waste management (SWM) is an integral component of civil infrastructure and the global economy, and is a growing concern due to increases in population, urbanization, and economic development. In 2011, 1.3 billion metric tons of municipal solid waste (MSW) were generated, and this is expected to grow to 2.2 billion metric tons by 2025. In the U.S., MSW systems processed approximately 250 million tons of waste and produced 118 Tg of CO_2e emissions, which represents over 8% of non-energy related greenhouse gas (GHG) emissions, and 2% of total net GHG emissions. While previous research has applied environmental life cycle assessment (LCA) to SWM using formal search techniques, existing models are either not readily generalizable and scalable, or optimize only a single time period and do not consider changes likely to affect SWM over time, such as new policy and technology innovation. This paper presents the first life cycle-based framework to optimize—over multiple time stages—the collection and treatment of all waste materials from curb to final disposal by minimizing cost or environmental impacts while considering user-defined emissions and waste diversion constraints. In addition, the framework is designed to be responsive to future changes in energy and GHG prices. This framework considers the use of existing SWM infrastructure as well as the deployment and utilization of new infrastructure. Several scenarios, considering cost, diversion, and GHG emissions, are analyzed in a 3-stage test system. The results show the utility of the multi-stage framework and the insights that can be gained from using such a framework. The framework was also used to solve a larger SWM system; the results show that the framework solves in reasonable time using typical hardware and readily available mathematical programming solvers. The framework is intended to inform SWM by considering costs, environmental impacts, and policy constraints.

1. Introduction

The World Bank estimates that 1.3 billion tons of municipal solid waste (MSW) are currently generated annually, and that this will grow to 2.2 billion tons by 2025 due to increases in population, urbanization, and economic development (World Bank, 2012). In 2011, U.S. municipal solid waste (MSW) systems processed approximately 250 million tons of waste. Approximately 54% of this waste was disposed in landfills, which are currently estimated to be the third largest source of anthropogenic methane in the U.S. behind natural gas systems and enteric fermentation (U.S. EPA, 2013a, 2013b). Of the 46% of MSW that is not landfilled, 58% is recycled, 18% is composted, and the rest is combusted for energy (U.S. EPA, 2013a). The direct emissions from landfilling, composting, and combustion of waste resulted in an estimated 118 Tg of CO_2e emissions, representing over 8% of non-energy related greenhouse gas (GHG) emissions, and 2% of net GHG emissions (U.S. EPA, 2013b). MSW also contains significant quantities of recoverable materials and can be used for energy recovery, making the SWM system a highly visible and potentially high-impact target for enhancing environmental sustainability. Possible future GHG mitigation policies are likely to impact the cost and strategic direction of SWM.

Given the complexity of SWM, even subtle changes to SWM programs pose potential for unintended environmental consequences. The appropriate selection of waste processing technologies and efficient waste management strategies offer opportunities to minimize environmental impacts, particularly through energy and materials recovery. An effective SWM strategy must account for the complex interdependencies and interactions among waste handling processes (e.g., collection, material recovery, biological and thermal treatment, and landfilling) and their effects on competing management objectives (e.g., minimize cost, maximize net energy production, increase waste diversion from landfills, and

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minimize GHG emissions). The framework presented here is intended to optimize integrated SWM decisions at the solid waste system level (e.g., municipality or county), but the results of these system level analyses could be aggregated to analyze larger jurisdictions (e.g., state, provincial, regional, or national).

Life cycle assessment (LCA) is a useful tool for systematically estimating the environmental impacts associated with SWM processes and systems (Björklund et al., 2010). Several LCA models have been developed to determine the environmental impacts associated with SWM systems (e.g., Dalemo et al., 1997; McDougall et al., 2001; Haight, 2004; Kirkeby et al., 2006). These models estimate the environmental impacts of various waste management alternatives, and can be used to perform "what-if" scenario analyses to quantify the environmental effects of incremental changes to the integrated system. While these models are an essential foundation that enables a systematic integrated analysis of SWM systems, they cannot simultaneously consider all possible waste collection and treatment alternatives to find the combination of technologies that optimizes environmental and economic objectives.

A number of optimization models have been developed to address various issues in SWM (e.g., Wang et al., 2012; Yanpeng et al., 2007; Costi et al., 2004), but only limited research in LCA-based optimization of integrated SWM has been reported (e.g., Harrison et al., 2001; Solano et al., 2002; Shmelev and Powell, 2006; Hung et al., 2007). Previous research has generally focused on single-stage analyses that assume static systems, although real-world SWM strategies must adapt to population and policy changes as well as changes to waste generation and composition. While some previous research efforts have considered stage-wise decision-making in SWM (e.g., Li et al., 2006; Li and Huang, 2007; Tan et al., 2010), they were not LCA frameworks, and they focused on relatively simple systems (e.g., a single or limited number of waste materials, a limited number of waste collection alternatives, little or no waste separation) without consideration of full life cycle emissions, and involved computationally demanding solution procedures (e.g., fuzzy quadratic programming, interval-parameter stochastic integer programming, inexact dynamic programming containing fuzzy boundary intervals). These approaches work well for small illustrative systems, but are not readily generalizable and scalable to larger systems and LCA modeling.

There are several bottom-up, technology explicit energy system models that are conceptually similar to SWOLF, such as the NEMS (EIA, 2009), MARKAL/TIMES (ETSAP, 2013), OSeMOSYS (Howells et al., 2011), and Temoa (Hunter et al., 2013). Such models represent individual technologies with a set of technical and economic characteristics, and technologies are linked to one another via model constraints representing the flow of energy commodities. These models minimize cost over a multi-decade horizon by optimizing the installed capacity and commodity flow among all technologies. However, none of these energy system models claim to also be LCA models with clearly defined system boundaries and a consistent functional unit that carries through the entire energy system network.

Prior work has not addressed changes in energy infrastructure in response to evolving environmental policy and technological innovation that may affect the performance of SWM. Changes in the broader energy system due to changes in the national and regional electricity generation mix will affect the prices of fuel and electricity used in SWM as well as the emissions associated with electricity use. For example, replacing coal-fired electricity generation with natural gas or renewables will change the emissions associated with electricity use. Since SWM infrastructure is often in operation for decades, it is essential that integrated SWM models provide useful insights into how such changes affect SWM. Long-term changes to the energy system, which involve the slow turnover of long-lived capacity, motivate the development of a multi-stage optimization of SWM.

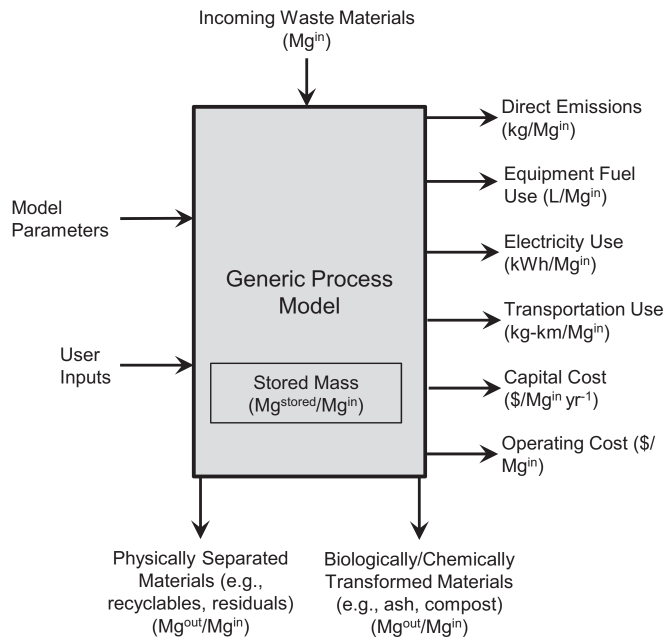

Fig. 1. Inputs and outputs for a generic waste treatment process model. Input masses and all outputs are specified per unit mass of each waste material. Model parameters and user inputs are used to characterize the transformation of the incoming waste mass as well as the resulting emissions, fuel use and costs. Users must specify the model parameters that are system-specific, while default values are available for other model parameters. 1 Mg = 1 metric ton.

A general modeling framework is needed to more realistically represent actual SWM management systems, which include dozens of waste streams, varying generation sector types, dozens of potential collection and treatment processes, and multiple time stages. This paper presents the Solid Waste Optimization Life Cycle Framework (SWOLF), which is suitable for stage-wise decision support under different scenarios. SWOLF is capable of developing integrated SWM strategies that consider existing as well as new SWM infrastructure. This is a major advantage since the reduced incremental costs associated with continued use of existing infrastructure is often an important factor in long-term capital decision making. Section 2 describes the modeling framework and includes an illustrative example that demonstrates the capability of the framework to represent complex SWM systems. Section 3 describes a simple test system, which is used to help illustrate the mathematical description of the optimization model in Section 4. Section 5 presents a simple, illustrative analysis using the test system described in Section 3, and Section 5.3 draws conclusions from the model formulation and application.

2. Integrated solid waste management modeling framework

2.1. Life cycle assessment framework for solid waste management

The functional unit for this LCA is the total mass of mixed MSW set out at the curb in a SWM system (e.g., municipality or county) over a specified decision horizon. The functional unit does not include items reused or treated by the waste generator (e.g., clothing used as rags, food waste treated in a garbage disposal, onsite composting). The basis of the framework is an LCA of an integrated SWM system that includes unit process models for