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# Simulation-based Optimization of Solid Waste Management and Recycling Programs

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## Abstract

Solid waste produced as a by-product of our daily activities poses a major threat to societies as populations grow and economic development advances. Consequently, the effective management of solid waste has become a matter of critical importance for communities. In this study, we propose a simulation-based decision-making and optimization framework for the analysis and development of effective solid waste management and recycling programs, under uncertainty. The components of the proposed framework include a database and two modules: an assessment module and a resource allocation optimization module. The assessment module identifies the sources of uncertainties in the system and develops a parameterization of them for incorporation into the resource allocation optimization module. This module involves a discrete-continuous model of the system under consideration, with respect to the waste types and characteristics, costs, environmental impacts, types, location and capacities of processing facilities, and their capabilities. Then, the multi-criteria problem of the allocation of limited resources is solved via the optimization mechanism embedded in the resource allocation optimization module. Here, the optimum solution is defined by the user and infinitely variable. The proposed decision making framework has been successfully demonstrated for the Miami-Dade County Solid Waste Management System in the State of Florida.

## Keywords
Discrete-continuous modeling of large-scale systems, sustainability and recycling, heuristic optimization, solid waste management

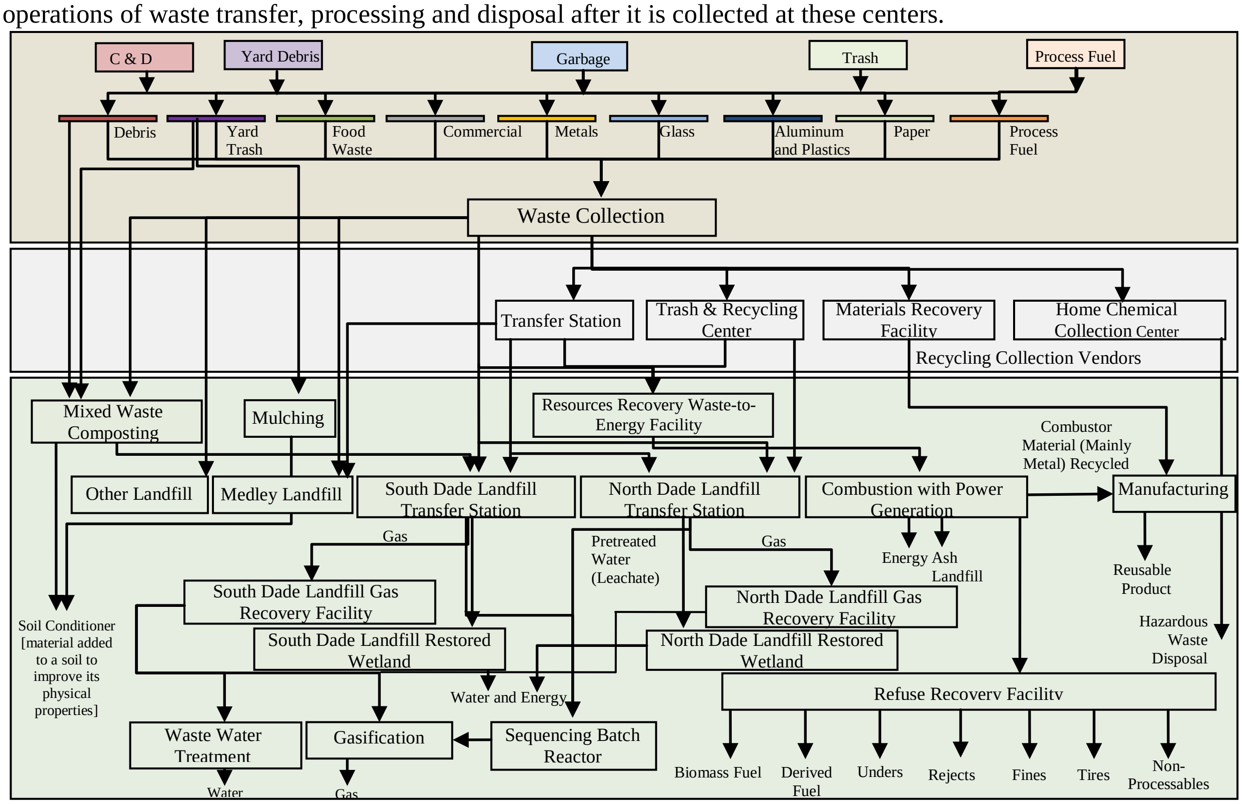
## 1. Introduction
Over the past decade, the rapid increase in both the volume and diversity of municipal solid waste, triggered by population growth, economic development, urbanization, and industrialization in U.S. and across the world, has become a threat for public health. In 2006, the total amount of municipal solid waste (MSW) generated globally reached 2.02 billion tons [1]. It is further estimated that after 2010, global generation of municipal waste will exhibit approximately a 9% increase per year. The growing significance of this problem has led national, state, and municipal governments to search for ways to ensure effective and sustainable management of municipal solid waste, including reduction, diversion, and recycling.

In the 2008 legislative session, Florida's statewide recycling goal was ambitiously set to 75%, to be reached by 2020, with annual municipal solid waste generation in Florida of 32 million tons [2]. While the State of Florida is taking legislative action to foster increased community awareness of the solid waste management problem, there are still major technical challenges to be overcome in order to successfully address the waste-related decisions in an integrated manner. First, the characteristics of a spectrum of solid waste management options, including voluntary and mandatory recycling, diversion programs, alternative waste processing [3], methods of transportation, and monitoring of the waste materials must be identified, and the best alternatives need to be selected for different areas. It should be noted here that the optimum waste management option, in terms of the conflicting objectives of minimizing cost and environmental impacts, may vary widely between regions. Additionally, the uncertainties associated with many system parameters, such as waste generation rates, facility capacities, diversion goals, and waste treatment costs, as well as their interrelationships [4] must be accurately captured within these management options. The uncertainties related to the transit of discarded or recycled materials through various stages in solid waste management systems must be quantitatively attained via defined parameters, where each of these stages poses uncertainties at different scales and scopes. Furthermore, multiple stakeholders are interested in the performance of the solid waste management system from diverse economic, technological, and environmental perspectives. Hence, the identification of economically sound and environmentally responsible management plans, that both satisfy the physical system constraints and align the conflicting objectives of multiple stakeholders becomes a challenging yet crucial task, necessitating the aid of comprehensive system-analysis methods and optimization techniques.

In order to remedy the challenges mentioned above, in this study we propose an advanced decision-support framework with reasonable computational burden, to reflect complex uncertainties and management issues, such as recourse actions and capacity allocations and extensions. A simulation-based optimization framework for the planning of effective waste reduction, diversion, and recycling programs is developed for supporting municipal solid waste management. The proposed framework includes a database, an assessment module, and a resource allocation optimization module, which is based on simulation-based optimization, and includes a discrete-continuous model of the system under review, combined with an embedded optimization mechanism. The multi-criteria objective of the optimization tool captures the economic and environmental goals singlehandedly, while the decision variables search for the optimal combination of management plans from multiple feasible alternatives for each stage of flow through the system (various options exist for planners to choose from at each stage).

## 2. Case Study: Solid Waste Management System of Miami-Dade County

In Miami-Dade County's integrated solid waste management system (DSWM), the solid waste generated by residents and businesses is collected via two systems: residential drop-off and curbside or scheduled collection. In the residential drop-off system, residents take hazardous household wastes (i.e. chemicals, batteries, fluorescent bulbs, etc.) to one of two Home Chemical Collection Centers, while they must take household trash, yard debris, white goods, and other wastes to one of 13 Trash and Recycling Centers (TRC's). The waste collected at these centers is directly transferred to the disposal system for final processing. This research concerns itself with the operations of waste transfer, processing and disposal after it is collected at these centers.




***Notes: 1. Total Waste: 3,982,082 tons; Recyclable: 690,557(17.73%); Waste: 3,291,525(82.27%)***
***2. Garbage contains trash and food waste. The amount of trash is calculated by dividing the sum of commercial waste, metal, glass, Aluminum and plastic, and paper in half. The total amount of garbage equals the sum of trash and food waste.***

Legend: Collection; Waste Transfer; Waste Disposal

Figure 1: Mass flow diagram for Miami-Dade County's current solid waste management system

In the waste stream, some recyclable materials go to the Material Recovery Facility, which is owned by Waste Management, Inc., a private company under contract with Dade County. Here, mixed recyclables are sorted, packed, and prepared for sale as raw material. The remainder of waste from curbside and scheduled collection is delivered to a transfer station, landfill, or the county's Resources Recovery Facility (RRF) (a refuse derived fuel waste-to-energy plant).. From the transfer stations, materials are delivered to either the county's RRF or one of its two landfills. At the RRF, waste is either lightly processed into a fuel, which is combusted on site to produce electricity, or is converted into a biomass product, which is sold. The ash of combustion is delivered to an onsite monofill facility.

## 3. Proposed Methodology

### 3.1 Overview of the Proposed Simulation-Based Decision-Making Framework

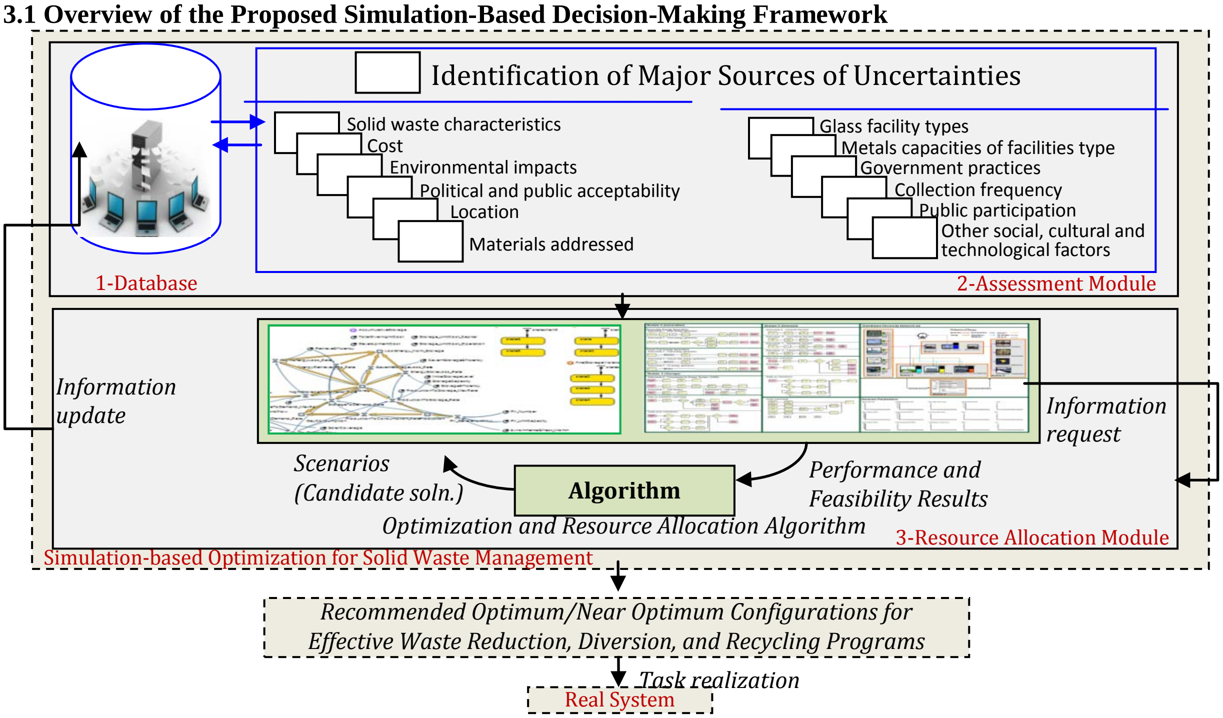



Figure 2: Proposed simulation-based decision making framework for effective solid waste management

In this study, we propose to develop a simulation-based decision optimization framework for solid waste management and recycling planning in Miami-Dade County, FL, with an objective to achieve the highest recycling rate while balancing both financial and environmental responsibilities. The proposed framework will be comprised of three major components: a database, an assessment module, and a resource allocation optimization module (see Figure 2).The database stores historical data, and filters noise out of the data. As coherent large-scale solid waste management systems are rare (especially in conjunction with waste collection, diversion and recycling operations), obtaining realistic data presented an additional challenge to the proposed modeling approaches. In this study, required historical data are gathered from several credible sources, including the Florida Department of Environmental Protection, the Miami-Dade County Department of Solid Waste Management, Waste Management, Inc., and current studies sponsored by the Hinkley Center. The data is retrieved from this database based on a parameterization, which is conducted by the assessment module. The parameterization is established by the formulation of optimization equations, elaborated in Section 3.3.5. Based on the relationship between the independent variables and dependent variables selected for manipulation at any given time, coefficients are obtained from the assessment module for use as our parameters and starting values, ensuring that the data from the real system and the simulation model are properly connected. In the resource allocation optimization module, parameters selected in the assessment module are used in the optimization equations and constraints to establish the new relationships. Here, we propose to develop a detailed simulation-based model of the solid waste management system in Dade County, Florida, using a combined discrete-continuous simulation modeling approach, and incorporating the parameters identified in the assessment module. The feedback received from the real system is used for the tuning of the proposed model, updating the databases, and enhancing the overall proposed tool for dynamic, data-driven adaptive solutions, as the system evolves and steers the measurement for selective data updates. This way, the proposed tool promises to perform not only for aggregate-level strategic management problems, but also for detail-level operational decisions in the future.

### 3.2Assessment Module

In the assessment module, the sources of uncertainty in the existing DSWM system are identified. Generation units (both residential and organizational), recyclable materials, and their associated cost for collection, processing, and transportation are detailed in this section. The major components of the solid waste management and recycling programs are highlighted below. These components are later analyzed quantitatively within the proposed simulation-based optimization model and comprise the basis for the variable set of the optimization mechanism. The large scale of the DSWM and other systems presented significant challenges in developing a concise yet complete parameterization of relevant parameters and uncertainties. The quality of such parameterization is critical for achieving accurate results in the following resource allocation optimization module while keeping computational burden within moderate bounds.

#### 3.2.1 Waste Producers, Types and Characteristics

The waste streams that enter the DSWM system can be broadly characterized as residential single family, residential multi-family, and business/institutional. The latter two receive scheduled pickup, while the former receives curbside pickup. The small number of residents who participate in the drop-off program will be considered constant. In this study, seven categories of solid waste are considered as shown below:

- *Construction and Demolition Debris (or C&D Debris)* consists of waste that is generated during the construction, renovation, and demolition of buildings, roads, and bridges.
- *Yard Trash* consists of vegetative matter produced by landscaping maintenance or land clearing operations. Yard trash comprises an average of 15-20% of the solid waste stream on an annual basis, and may be as much as 50% in some areas during the summer growing season.
- *Food Waste* includes all food substances, raw or cooked, which enter the waste stream. At present, the bulk of food waste produced in Miami-Dade County is either landfilled or incinerated.
- *Commercial Wastes* are divided into three categories in our program: tires, textiles, and miscellaneous products. At present, most commercial wastes in Miami-Dade County are sorted out of the main waste stream and handled by specialized contractors.
- *Metals* are unique in that, unlike other materials, they can be repeatedly recycled without degradation of their properties. Metal recycling is an established, popular, and economically advantageous process.
- *Glass* makes up a significant component of household and industrial waste due to its weight and density. Glass recycling is another established and economically lucrative form of recycling.
- *Aluminum and Plastics* is the category specifically for domestic and light commercial applications of these materials, namely for packaging, durable goods, and consumables.
- *Paper* and other paper-based materials are largely pulp-based, and like metal and plastic, historically have been successfully recycled on a large scale.

#### 3.2.2Processing and Operations

A broad variety of factors and facilities are involved in the processing and ultimate disposal of collected materials, which must be sorted by type, sent to processors, and then to market. Furthermore, materials must be transported between these various stages, non-recyclable materials must be removed and disposed of, and economic provisions must be in place for an effective (mutually beneficial) public-private partnership. Due to the short-term nature of Florida’s 75% recycling goal, this study first seeks the maximum allocative efficiency amongst existing facilities.

- *Markets* in Miami-Dade County, based on accepted materials, penalties for rejected loads, and net price, are considered in the evaluation of alternative programs. Consideration for the different types of markets is included in the optimization and resource allocation algorithm.
- *Composting* is the controlled decomposition of organic matter by microorganisms into a humus-like product. Composting is not used in Miami-Dade County on a large scale, therefore will be considered as part of the future work.
- *Refuse Derived Fuel* (RDF), is produced from a variety of combustible materials in the waste stream. An RDF plant selects materials with high heating value, and produces a fuel that can be sold to industries or burned on site. RDF and incineration are presently used in Miami-Dade County on a utility scale.
- *Landfills* are the final destination for materials not extracted from the waste stream for recycling or combustion for energy. Landfilling is a long-established method and is used in Miami-Dade County on a large scale. However, landfills have numerous long-term economic and environmental costs.

- *Bioreactors* are a hybrid of landfilling and composting methods. They rapidly reduce and degrade organic materials via additives that accelerate decomposition of organic materials. There are presently no utility-scale bioreactor operations in Dade County.

### 3.3 Resource Allocation and Optimization Module

The resource allocation optimization module consists of a simulation model incorporating all of the uncertainties identified in the assessment model. The model is built with an aim to represent the life cycle of different types of solid waste in a realistic simulation environment. To this end, the model details the differences in the life cycle processes (i.e., waste diversion, collection, transport, and disposal options) of various types of solid waste (i.e., yard trash, construction and demolition debris, glass etc.) and enables a performance analysis study on possible alternatives. In order to accurately capture the complex, dynamic, and heterogeneous character of SWM systems, the simulation-based optimization features a discrete-continuous simulation with robust capabilities for simulating uncertainties and an embedded optimization mechanism. The high levels of complexity and large scale characteristic of these systems creates significant challenges for the optimization mechanism, due to the size of the possible solution space. The optimization and resource allocation algorithm within this module initiates its operations by generating a candidate solution plan. This algorithm is developed based on meta-heuristics in order to reduce computational burden while enabling the desired accuracy level in the solution. The performance (in terms of cost, percentage of the recycling goal met, and the environmental impact) and effectiveness of this candidate solution plan (or scenario) is evaluated on a quantitative basis using the aforementioned discrete-continuous simulation model, and the procedure repeats itself as the algorithm searches through various candidate allocations. Finally, the same algorithm selects the solution with best performance to be executed and sent to the real system for implementation. The optimization and resource allocation algorithm enforces a multi-criteria approach, considering the conflicting goals of solid waste management involving social (high recycling value and high participation rates), economic (low financial cost), and environmental (low greenhouse gas emissions) objectives.

#### 3.3.1 Breakdown of Deliveries and Economic and Environmental Cost

As the DSWM system is the largest government-owned and operated waste collection and disposal system in the southeastern U.S., facility locations and service areas are spread widely across Miami-Dade County. There are 13 trash and recycling centers, three transfer stations, four landfill facilities, two home chemical collection centers, and theResources Recovery Facility (RRF, an RDF-based waste-to-energy plant). These facilities are separated by distances of as much as 50 miles. Mileage figures sent to the assessment module are based on the average distance of several routes between destinations, and time spent is based on averaged traffic conditions, but naturally varies.

The 2010 DSWM Annual Report indicates total arrivals of 3,982,082 tons of solid waste. Among these wastes, 989,339 tons were disposed at DSWM landfills, 1,146,016 tons were incinerated at the RRF, 1,869,861 tons were disposed at privately owned and operated landfills outside of DSWM's internal or contracted activities, and 128,668 tons were recycled at the MRF. This existing breakdown is sent to the assessment module and provides starting conditions for the optimization mechanism and simulation model.

DSWM provides a variety of services for residents, including curbside collection of garbage, trash, and recyclables. When considering the cost for providing such services, capital investments, operation costs, and collection and transportation costs must all be included. In addition, environmental costs may occur at any stage of the waste management lifecycle, and vary according to the disposal method used at the treatment and disposal stage. Table 1 details the values of these costs in four groups (construction, operation, transportation, and environmental).

#### 3.3.2 Continuous-Discrete Simulation Modeling of Integrated Solid Waste Management Systems

A continuous-discrete simulation-based model of the present DSWM system has been developed. This model is broadly divided into four regions, which simulate the major components of the real system: diversion, transport, disposal, and environmental discharges. The framework also relies on a database of sequences and schedules, which provide an operating infrastructure. Each facility, in addition to the transfer trucks, is represented in the framework as a resource. Each resource is assigned a schedule, which provides a weekly cycle of hours of operation, and capacities, which limits how much material it can process. All resources, except for the trucks, have two capacities, one of which is reset every 24 hours and represents daily capacity, and another which counts the inventory of material at the facility in real time, representing floating capacity.

The waste material flowing through the model is also provided with an infrastructure. The model includes 17 sequences, which describe all possible routes that the material can take through the system. All waste is assigned a sequence when it enters the model, which becomes an attribute of that particular unit of waste, and guides it through the various facilities. The sequences provide the trucking mechanism information as to the distance and time required for transfer, and increment facility usage and cost counters at the appropriate times and places. The sequences also ensure that all material on each transfer truck has the same destination. One of the most important decision variables the optimization mechanism will modify is the distribution of sequence assignments to incoming waste. When starting the model, delivery and disposal values entered by the user into the user form are used to establish the initial distribution of sequence assignments, based on a pro-rating system in which each disposal node's overall proportion is applied to the outflows of each delivery node, and an error-checking mechanism ensures that all decision points sum to 100%.

Table 1: Economic and Environmental Costs in Fiscal Year 2010

| Items | | Total Cost | Average Cost (per Ton) |
|---|---|---|---|
| Construction Costs | Capital Assets | 181,000,000 | |
| | Investment in 2010 | 2,500,000 | |
| Operation Costs | Landfills | 9,782,542 | 9.9 |
| | Transfer Stations | 18,811,824 | 34.0 |
| | Trash and Recycling Centers | 5,256,173 | 32.7 |
| | Home Chemical Collection Centers | 159,718 | 842.4 |
| | Resource Recovery Facility | 65,444,000 | 57.1 |
| | Material Recovery Facility | 8,424,000 | 65.5 |
| Collection Costs | | 58,053,000 | 14.6 |
| Transportation Costs | Fixed Cost (Hourly Labor) | | 14.3 |
| | Variable Cost | | 1.6 |
| Environmental Costs | Leachate Treatment | 1,595,377 | 0.4 |
| | Air Pollution Control | 4,320,000 | 1.1 |

In the diversion area, waste is produced as garbage, trash, yard debris, C&D debris, or process fuel entities. It is then assigned an attribute waste type (paper, metal, organic matter, etc.) based on what is included in its general entity. This material is then assigned one of the 17 sequences based on the distribution specified by the user form or under review by the optimization mechanism. These decisions occur instantaneously, and waste is produced at a consistent rate during the hours that collection trucks make deliveries. As waste leaves the diversion area, it is batched onto truckloads to the same delivery node in the transfer area.

The next area of the model includes the transport options. This area covers all transfer station, landfill, and RRF (waste-to-energy) operations. It is unique in that it is the only area that waste may pass through twice, on transfer station and landfill or resource recovery lines. As a batched group of waste arrives at its delivery node in this area, it is separated and sent to the processing block. At this point, the facility's capacity and cost counters are updated appropriately, and the waste emerges from the facility after the facility's designated processing time elapses. From there, it is batched by its next destination and sent either to another node in the transport options area, if it has not yet been landfilled or incinerated, or out of the transfer area if it has. When sent between nodes in the transport area, a transfer truck resource is seized for the duration of the transfer time assigned by the sequence, and released at the destination node, where it awaits another load or is sent empty to another location by the model, based on controls set by the optimization system.

Following the transport options area, waste enters the disposal options area. Here it is separated from batches for the final time, passes through the process blocks for the disposal schemes indicated by its assigned sequence, and concludes its counter for processing time. As the time required for landfilling and incineration is captured when facility resources are seized in the transport options area, processes in the disposal options area are instantaneous. Following the disposal options area, waste moves to the environmental discharges section, the final portion of the model. Here, the various discharges for each disposal scheme, such as electricity, ash, landfill gas, leachate, and carbon dioxide gas, per unit of waste processed, are activated and added to the appropriate counters, prior to disposal of model entities. Throughout the model, counters at numerous process blocks, either incremented at the blocks or via sequences, are used as indicators sent to the optimization framework. They provide a wealth of feedback on the performance, cost, and environmental discharges of the candidate set of decision variables. The specific optimization values and formulation are described in Section 3.3.3.

**3.3.3 Formulation of the Optimization Problem**

The objective of the proposed decision making framework is to determine the near optimal plans for solid waste management and recycling programs, in terms of minimizing cost and maximizing environmental and social benefits. An optimized SWM system is achieved by defining the flows to be sent to various recycling, processing, and disposal facilities, and identifying the near-optimal number of facilities of each type to be activated. The proposed framework can optimize SWM systems for any objective, including but not limited to minimizing cost and maximizing recycling. In this section, the mathematical formulation for the aforementioned optimization problem, including its decision variables, constraints, and objectives, is established.

In our initial formulation of the problem, we have considered nine categories of materials, denoted by the index i where $i \in I = \{1,..,9\}$.Here, the numbers 1 through 9 represent construction and demolition debris, yard trash, food wastes, commercial products (tires, textiles, and miscellaneous), metals (ferrous and non-ferrous), glass, aluminum and plastics, paper, and process fuel, respectively. The total daily production of solid waste is represented by$Q$ and the daily waste generated for material of type $i$is denoted as$q_i$. However, the process varies depending on whether, and to what extent, these materials are presorted prior to collection. The material flows to be sent to the MRF are recycled, and the balance of the refuse flow can be directed to a transfer station, a trash and recycling center, the RRF, a home chemical collection center, or a landfill. Here, those disposal facilities are denoted by the set of$j \in \{1,..,J\}$, $k \in \{1,..,K\}$$p \in \{1,..,P\}$,where$J = K = P = 22$, in which the numbers 1 through 22 represent collection, the transfer stations, the trash and recycling centers, the material recovery facilities, the home chemical centers, mulching facilities (negligible in present DSWM system), composting facilities (negligible in present DSWM system), the RRF, the Medley Landfill, the South Dade Landfill (and transfer station), the North Dade Landfill (and transfer station), manufacturing plants, the South Dade Landfill Gas Recovery Facility, the North Dade Landfill Gas Recovery Facility, the sequencing batch reactor (for landfill leachates), the South Dade Landfill Restored Wetland, the North Dade Landfill Restored Wetland, the Refuse Recovery Facility(at the RRF), waste water treatment plants, and gasification plants, respectively (see Figure 1). We introduce the decision variable$x_{i,j,t}$ to denote the amount of waste type $i$ carried to processing facility $j$ at time $t$, $y_{j,k,t}$to denote the waste transferred amount among the processing facilities at time $t$, and $m_{j,t-1}$ to denote the inventory of solid waste stored in the processing facility $j$at time$t-1$, where$t \in T$ represents the time period. The RRF, and any other refuse-derived-fuel plants, further separates the incoming refuse between materials that can be converted into RDF for incineration or sale and materials that cannot be used for fuel production, which are discharged as byproducts. Discharge types are represented by index $l$ where $l \in L = \{1,..,14\}$in which the numbers 1 through 14 represent soil conditioner, water, energy, gas, biomass fuel, derived fuel, unders, rejects, fines, tires, non-processables, ash, reusable products, and hazardous waste, respectively. Decision variables$z_{j,l,t}$represent the amount of materialcarried from processing node $j$to discharge node $l$ at time $t$, respectively. Therefore, it should be noted that the proposed model contains both binary and continuous variables.

The cost objective is defined as the minimization of the overall costs for solid waste management and recycling operations, as encoded in Eq. (1). In Eq. (1), TC represents total cost, including construction cost($C_c$), recycling and collection costs ($C_r$), transportation costs ($C_t$),maintenance costs ($C_m$), processing costs ($C_p$), discharge costs ($C_d$), as well as the expected gains and profits (G) that can be made as a result of the sale of RDF and electrical energy produced. Detailed formation of the$C_r$, $C_t$, $C_p$, $C_d$are defined in Eq. (2) and Eq. (3) where $C_{i,j}^{Coll}$ is the per-unit collection cost of waste type $i$ that is brought to processing facility $j$, $C_{j,k}^{Trans}$is the per-unit transport cost between processing facilities$j$ and $k$, $C_j^{Proc}$ is the per-unit processing cost of processing facility $j$, $C_{j,l}^{Disch}$ is the per-unit discharging cost of discharge type $l$from processing facility$j$. In this work, we mainly focus on the optimization of the costs, and use the historical data as a fixed variable of the profits.

$$Z_1 = Min\ TC = C_c + C_r + C_t + C_p + C_d + C_m - G \tag{1}$$

$$C_r = \sum_{t\in T}\sum_{j=1}^{1}\sum_{i=1}^{9} C_{i,j}^{Coll} x_{i,j,t}\ ; \qquad C_t = \sum_{t\in T}\sum_{k=j+1}^{22}\sum_{j=1}^{22} C_{j,k}^{Trans} y_{j,k,t} \tag{2}$$

$$C_p = \sum_{j=1}^{22} C_j^{Procs} y_j; \qquad C_d = \sum_{t\in T}\sum_{l=1}^{14}\sum_{j=1}^{22} C_{j,l}^{Disch} z_{j,l,t} \tag{3}$$

In regard to the environmental objective, the life cycle inventory (LCI) values of the greenhouse gases CO, CO2, NOx, and SOx, are calculated for each unit process by individual waste component. The emissions are expressed in terms of mass of gas generated per ton of material processed at each unit process. Similarly, the energy consumed is computed in terms of BTU consumed by processing one ton of waste at a given unit process. The environmental emissions and leachates objective is defined as the following Eq. (4) where $w_j^{leachate}$ represents the amount of leachate discharged from facility $j$.

$$Z_2 = Min\ \sum_{e\in\{CO,CO2,NOx,SO2\}} LCI(e) + \sum_{j\in J} w_j^{leachate} \tag{4}$$

In regard to constraints of the defined optimization problem, mass balance equations, normative constraints, technical constraints for plant capacities and contractual minimums, constraints imposing the presence of plants, and bounds on the flows entering different types of plants are amongst the constraints that must be considered as part of the mathematical formulation of effective solid waste management solutions.

$$\sum_{i=1}^{9} x_{i,1,t-1} - \sum_{k=2}^{12} y_{1,k,t-1} = m_{1,t-1} \tag{5}$$

$$y_{1,2,t-1} - y_{2,8,t-1} - \sum_{j=10}^{12} y_{2,j,t-1} = m_{2,t-1}; \quad y_{1,3,t-1} - y_{3,8,t-1} - \sum_{k=10}^{11} y_{3,k,t-1} = m_{3,t-1} \tag{6}$$

$$y_{1,4,t-1} - y_{4,14,t-1} = m_{4,t-1}; \quad y_{1,5,t-1} - z_{5,14,t-1} = m_{5,t-1} \tag{7}$$

$$x_{2,6,t-1} + y_{1,6,t-1} - z_{6,1,t-1} = m_{6,t-1} \tag{8}$$

$$x_{1,7,t-1} + x_{2,7,t-1} + y_{1,7,t-1} - y_{7,11,t-1} - z_{7,1,t-1} = m_{7,t-1} \tag{9}$$

$$\sum_{j=1}^{3} y_{j,8,t-1} - y_{8,13,t-1} = m_{8,t-1} \tag{10}$$

$$\sum_{j=1}^{3} y_{j,11,t-1} + y_{7,11,t-1} - y_{11,15,t-1} - y_{11,17,t-1} - y_{11,18,t-1} = m_{11,t-1} \tag{11}$$

$$\sum_{j=1}^{3} y_{j,12,t-1} - y_{12,16,t-1} - y_{12,17,t-1} - y_{12,19,t-1} = m_{12,t-1} \tag{12}$$

$$y_{8,13,t-1} - y_{13,20,t-1} - y_{13,22,t-1} - z_{13,3,t-1} - z_{13,12,t-1} = m_{13,t-1} \tag{13}$$

$$y_{4,14,t-1} + y_{13,14,t-1} - z_{14,13,t-1} = m_{14,t-1}; \quad y_{11,15,t-1} - y_{15,21,t-1} - y_{15,22,t-1} - z_{15,3,t-1} = m_{15,t-1} \tag{14}$$

$$y_{12,16,t-1} - y_{16,21,t-1} - y_{16,22,t-1} - z_{16,3,t-1} = m_{16,t-1}; \quad y_{11,17,t-1} + y_{12,17,t-1} - z_{17,21,t-1} = m_{17,t-1} \tag{15}$$

$$y_{11,18,t-1} - z_{18,2,t-1} - z_{18,3,t-1} = m_{18,t-1}; \quad y_{12,19,t-1} - z_{19,2,t-1} - z_{19,3,t-1} = m_{19,t-1} \tag{16}$$

$$y_{13,20,t-1} - \sum_{l=5}^{11} z_{20,l,t-1} = m_{20,t-1} \tag{17}$$

$$y_{15,21,t-1} + y_{16,21,t-1} + y_{17,21,t-1} - z_{21,2,t-1} = m_{21,t-1} \tag{18}$$

$$y_{13,22,t-1} + y_{15,22,t-1} + y_{16,22,t-1} - z_{22,4,t-1} = m_{22,t-1} \tag{19}$$

Eqs.(5)-(19) show the input-output constraints on the solid waste management system. Eq. (5) represents the input-output constraints on the collection facilities. After all waste types are collected by the various collection methods, the collected waste is delivered to transfer stations, trash and recycling centers, material recovery facilities, home chemical collection centers, and mulching and composting facilities. The waste delivered to the transfer stations and trash and recycling centers is then transferred to the landfills and the RRF, as in Eq. (6). Waste coming into the material recovery facility (MRF) is delivered to manufacturing facilities for reuse, as in Eq. (7). Materials brought to home chemical collection centers are handled by specialized contractors and are sent to disposal or manufacturing facilities for reuse, as in Eq. (8). Eq. (9) indicates that the input into mulching equals to the sum of its inventory and its discharge of soil conditioner. Eq. (10) indicates that the input into mixed waste composting equals its stored inventory and discharged soil conditioner. The input into the RRF equals its inventory and the material combusted for power generation, as in Eq. (11). The waste processed at landfill transfer stations goes to the sequencing batch reactor, landfill gas recovery facility, and restored wetlands as in Eq. (12) and (13). Eqs. (14)- (19) represent that the input into the processing facilities is equal to the discharge amounts. Eqs. (20)-(33) reflect the capacity constraints at the processing and disposal facilities, where $Cap_j^{max}$ is the maximum capacity for facility $j$.

$$\sum_{i=1}^{9} x_{i,1,t} + m_{1,t-1} \le Cap_1^{max}; \quad y_{1,2,t} + m_{2,t-1} \le Cap_2^{max} \tag{20}$$

$$y_{1,3,t} + m_{3,t-1} \le Cap_3^{max}; \quad y_{1,4,t} + m_{4,t-1} \le Cap_4^{max} \tag{21}$$

$$y_{1,5,t} + m_{5,t-1} \le Cap_5^{max}; \quad x_{2,6,t} + y_{1,6,t} + m_{6,t-1} \le Cap_6^{max} \tag{22}$$

$$x_{1,7,t} + x_{2,7,t} + y_{1,7,t} + m_{7,t-1} \le Cap_7^{max}; \quad y_{1,8,t} + y_{2,8,t} + y_{3,8} + m_{8,t-1} \le Cap_8^{max} \tag{23}$$

$$y_{1,9,t} + m_{9,t-1} \le Cap_9^{max}; \quad y_{1,10,t} + y_{2,10,t} + m_{10,t-1} \le Cap_{10}^{max} \tag{24}$$

$$\sum_{j=1}^{3} y_{i,11,t-1} + y_{7,11,t-1} + m_{11,t-1} \le Cap_{11}^{max}; \quad \sum_{j=1}^{3} y_{i,12,t-1} + m_{12,t-1} \le Cap_{12}^{max} \tag{25}$$

$$y_{8,13,t-1} + m_{13,t-1} \le Cap_{13}^{max}; \quad y_{4,14,t-1} + y_{13,14,t-1} + m_{14,t-1} \le Cap_{14}^{max} \tag{26}$$

$$y_{11,15,t-1} + m_{15,t-1} \le Cap_{15}^{max}; \quad y_{12,16,t-1} + m_{16,t-1} \le Cap_{16}^{max} \tag{27}$$

$$y_{11,17,t-1} + y_{12,17,t-1} + m_{17,t-1} \le Cap_{17}^{max}; \quad y_{11,18,t-1} + m_{18,t-1} \le Cap_{18}^{max} \tag{28}$$

$$y_{12,19,t-1} + m_{19,t-1} \le Cap_{19}^{max}; \quad y_{13,20,t-1} + m_{20,t-1} \le Cap_{20}^{max} \tag{29}$$

$$y_{15,21,t-1} + y_{16,21,t-1} + y_{17,21,t-1} + m_{21,t-1} \le Cap_{21}^{max} \tag{30}$$

$$y_{13,22,t-1} + y_{15,22,t-1} + y_{16,22,t-1} + m_{22,t-1} \le Cap_{22}^{max} \tag{31}$$

$$m_{j,t-1} + \sum_{i=1}^{9} x_{i,j,t} + \sum_{k=1}^{22} y_{k,j,t} = m_{j,t} + \sum_{p=1}^{22} y_{j,p,t} + \sum_{l=1}^{14} z_{j,l,t}, \quad \forall j \ne k \ne p \tag{32}$$

$$\forall x_{i,j,t-1} \geq 0; \quad \forall y_{j,k,t-1} \geq 0; \quad \forall z_{j,l,t-1} > 0; \forall m_{j,t-1} \geq 0 \tag{33}$$

## 4. Experiments and results

Experiments were conducted using the Rockwell Arena software package on a Virtual Computing (Cloud) System. A total of 6 scenarios were considered, each for time periods of 3, 6, 9, and 12 years. The optimization mechanism was run for 300 iterations of each scenario-duration combination, and each iteration was repeated 3 times. The first four scenarios optimized the present system under a constant demand (waste production). These conditions were evaluated both with cost minimizing and recycling maximizing objectives, respectively, and with capacity constraints lifted and in place, respectively. With capacity constraints lifted, the optimization mechanism attempted to maximize flows to landfills for the cost-minimizing objective, and to maximize flows to the RRF for the recycling-maximizing objective. The former result is due to the fact that landfills were the least expensive disposal option available. The latter result is observed due to the fact that the RRF is the only facility which produces a stream of recyclables, from its on-site Refuse Recovery Facility. However, despite this behavior, the optimization mechanism did not send 100% of the waste stream to landfills in the former and to the RRF in the latter, despite the absence of capacity limitations. This is due to the presence of lower and upper bounds on each decision variable in the optimization mechanism.

For the scenarios with capacity constraints in place (scenarios 3 and 4), which served as the framework's validation trials, average annual costs and recycling rates are held constant at all run durations in each scenario, and no significant inconsistencies appear. The consistency of data within and between scenarios corroborates the quality and accuracy of the framework, and indicates suitability for long-term strategic planning purposes. Averaged annual costs and recycling rates between these two scenarios were much closer than they were between the former two. This is reflective of the significant limitations that capacity constraints apply to both the framework and real system. These limitations are exacerbated by the high capacity utilization characteristic of SWM infrastructure, and reduce the ability of the optimization mechanism to apply the objective, as capacity feasibly is required. This finding reveals that for the purposes of the case study in Miami-Dade County, recycling rates cannot be improved to the extent required by the Florida 2020 goal exclusively by manipulating existing disposal infrastructure, as the framework was confined to throughout the experiments. However, the data does reveal the suitability of the framework to prepare such long term plans given various infrastructure enhancements or collection changes to review, material for future venues or applications.

In scenarios 5 and 6, demand (waste production) was increased 3% annually, while capacities were held constant, and capacity constraints are enforced. The results have shown a fairly linear increase in costs with demand, and recycling rates are maintained despite the high capacity utilization at the onset. This highlights the framework's capacity to analyze all available candidates under each new scenario, and thus maximize the utility of available resources to meet dynamic needs. However, there is little difference in the data from these two scenarios, as with the prior two scenarios, due to the capacity limitations. Furthermore, as the average annual mass recycled increases more slowly than demand, it is manifest that RRF capacity is exhausted and the optimization is utilizing all available resources to feasibly manage the increasing demand, reducing the impact of the objective. This suggests that, provided demand increases at 3% annually, the present DSWM infrastructure will reach its maximum capacity, despite optimization, in somewhat more than 12 years.

## 5. Conclusions and Future Work

In this study, an effective simulation-based decision-making and optimization framework has been developed for integrated solid waste management and recycling systems, analyzing both their economic and environmental aspects. The Miami-Dade County Department of Solid Waste Management is selected as a case study for this framework, and the proposed tool provided recommendations to the real system, pursuant to achieving the State of Florida's 75% recycling goal by the year 2020.

The proposed framework consists of a database of collected historical data, an assessment module for the representation of the current SWM system's decision variables and points of uncertainty, and a resource allocation optimization module, featuring a continuous-discrete simulation of the current system and an embedded optimization solution. The preliminary results obtained from the proposed framework provide the system with a set of near optimal resource allocation recommendations in terms of the refuse to be distributed amongst current facilities. Experiments have shown that the framework successfully handled rising demand with fixed capacity, while keeping cost increases linear and maintaining capacity feasibility. The framework also successfully analyzed proposed capacity increases, although for the case study, it found them to be of minimal benefit to reduce costs or increase recycling rates. The findings of the experiments also suggest that the framework would be of utility in calculating max-out dates for infrastructure under dynamic demand, and in analyzing changes to retard max-out.

Table 2: Results for Scenario 1 through 6

| Scenario | Planning Horizon (Years) | Average waste processed (Million Tons) | Average waste recycled (Million Tons) | Average cost (Million) | Average annual waste processed (Million Tons) | Average annual waste recycled (Million Tons) | Average annual cost (Million) | Average annual recycling rate |
|---|---|---|---|---|---|---|---|---|
| 1: no constraints, objective to min. cost | 3 | 5.93 | 1.14 | $228.5 | 1.98 | 0.38 | $76.2 | 19.15% |
| | 6 | 11.84 | 2.48 | $564.8 | 1.97 | 0.41 | $94.1 | 20.97% |
| | 9 | 17.87 | 3.91 | $880.4 | 1.99 | 0.43 | $97.8 | 21.90% |
| | 12 | 23.84 | 4.75 | $882.2 | 1.99 | 0.40 | $73.5 | 19.92 |
| 2: no constraints, objective to max. recycling | 3 | 6.01 | 1.61 | $523.4 | 2.00 | 0.54 | $174.5 | 26.83% |
| | 6 | 12.02 | 3.22 | $1,045.9 | 2.00 | 0.54 | $174.3 | 26.78% |
| | 9 | 17.99 | 4.82 | $1,566.2 | 2.00 | 0.54 | $174.0 | 26.78% |
| | 12 | 23.95 | 6.43 | $2,085.2 | 2.00 | 0.54 | $173.8 | 26.84% |
| 3: real constraints, objective to min. cost | 3 | 5.91 | 1.53 | $344.3 | 1.97 | 0.51 | $114.8 | 25.88% |
| | 6 | 11.91 | 3.07 | $701.1 | 1.99 | 0.51 | $116.9 | 25.79% |
| | 9 | 17.80 | 4.60 | $1,032.4 | 1.98 | 0.51 | $114.7 | 25.87% |
| | 12 | 23.80 | 6.16 | $1,384.5 | 1.98 | 0.51 | $115.4 | 25.90% |
| 4: real constraints, objective to max. recycling | 3 | 6.01 | 1.57 | $356.6 | 2.00 | 0.52 | $118.9 | 26.17% |
| | 6 | 11.96 | 3.13 | $710.1 | 1.99 | 0.52 | $118.3 | 26.19% |
| | 9 | 17.97 | 4.70 | $1,089.6 | 2.00 | 0.52 | $121.1 | 26.13% |
| | 12 | 23.94 | 6.26 | $1,421.3 | 1.99 | 0.52 | $118.4 | 26.16% |
| 5: 3% annual demand growth, objective to min. cost | 3 | 6.09 | 1.56 | $356.1 | 2.03 | 0.52 | $118.7M | 25.67% |
| | 6 | 12.75 | 3.29 | $741.3 | 2.12 | 0.55 | $123.5M | 25.83% |
| | 9 | 19.90 | 5.09 | $1169.7 | 2.21 | 0.57 | $130.0M | 25.59% |
| | 12 | 27.66 | 7.12 | $1610.3 | 2.30 | 0.59 | $134.2M | 25.77% |
| 6: 3% annual demand growth, objective to max. recycling | 3 | 6.17 | 1.62 | $366.4 | 2.06 | 0.54 | $122.1M | 26.17% |
| | 6 | 12.81 | 3.35 | $761.1 | 2.14 | 0.56 | $126.8M | 26.13% |
| | 9 | 20.04 | 5.24 | $1191.9 | 2.23 | 0.58 | $132.4M | 26.14% |
| | 12 | 27.67 | 7.23 | $1642.6 | 2.31 | 0.60 | $136.9M | 26.13% |

Future venues of this work include extending the scope of the case study from Miami-Dade County to neighboring Broward County, and eventually the entire State of Florida. Due to the vast scope and significant level of exchange between many counties in Florida, a modular simulation topology would be requisite for such a framework to be practical. A modular approach would provide a single decision-making tool suitable to local, regional, and state planning purposes. Modules would connect, interact, and exchange resources, by adhering to a standardized interface. Further potential venues of this project include the analysis of public recycling participation, collection methods and infrastructure, and the impact of public education programs, as well as enhanced transport coverage via an agent-based paradigm. The experiments have revealed that the optimization of existing disposal infrastructure will not enable Miami-Dade County to meet Florida's 75% recycling goal for 2020. Therefore, optimization of public participation programs and collection appear requisite for the framework to assist in reaching this goal.

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