Hybrid Simulation-based Planning and Evaluation Framework for Solid Waste Management and Recycling Systems

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Abstract

Over the past decades, the volume and diversity of municipal solid waste (MSW) generated by the United States have risen significantly. Together with increasing environmental regulations, these pressures have made solid waste management (SWM) a critical issue for communities. SWM systems are highly complex, requiring a variety of facilities and transfer mechanisms. Unlike many large-scale systems, both government agencies and private contractors work cooperatively with sophisticated network relationships in SWM systems. Thus, the characteristics of each facility, as well as uncertainties at both the facility and system levels, must be assessed and quantified prior to modeling. In light of the economic and environmental pressures facing municipalities, the necessity of modeling and optimization for decision support has become apparent. Therefore, a modular simulation and optimization framework is proposed, in which agent-based modeling captures multi-agent interactions and agent-specific objectives, while operation of treatment and disposal facilities are incorporated with discrete-event facility-level sub-models. This framework provides both global and facility performance monitoring and optimization, and has sufficient generality to be applicable to the SWM system of any region, based on database contents. The proposed framework has been successfully applied at both the county and region levels in the State of Florida.

Keywords
Modeling of large-scale systems, modular modeling, solid waste management, recycling programs, hybrid modeling

1. Introduction
The volume and diversity of municipal solid waste (MSW) generated worldwide has risen markedly over the past several decades, with the United States exhibiting the greatest rate of growth, overall and per-capita, by a significant margin. Together with this burgeoning growth, regulation of the environment and environmental discharges has increased as well, thus reducing the availability of disposal sites and increasing the cost of disposal. These stresses, acting in concert with the rising cost of virgin materials, have provided the impetus for the establishment of recycling programs throughout the United States. In 2008, the State of Florida set an ambitious recycling goal of 75%, to be achieved by the year 2020 [1]. Given Florida’s present recycling rate of 31%, as well as the fiscal difficulties befalling municipalities throughout the state, this goal presents significant technical and social challenges to a variety of parties, including the government, solid waste management utilities, and the waste generators. In Florida, solid waste management services are organized at the county level via integrated solid waste management (SWM) systems, which include the collection, transfer, disposal, and recycling of the entirety of the MSW generated by a given geographic region. Such an integrated SWM system is highly complex and includes many diverse components: fleets of collection and transfer vehicles, sorting and transfer facilities, recycling facilities, and disposal facilities. As a result of their complexity and inherently large scale, many stakeholders have vested interests in the performance of integrated SWM systems, including governments, regulators, public and private utilities, and generation units. Assessing the performance of integrated SWM systems is also a challenging and complex process [2, 3], as it covers many aspects, including cost, recycling rate, greenhouse gas emissions, etc. In addition to the highly prismatic nature of performance assessment, significant uncertainties are also present in integrated SWM systems, at both the facility (capacity availability) and system (day-to-day generation rates and delivery destinations).
levels. The combination of pervasive uncertainties and multi-faceted performance analysis make the optimization of integrated SWM systems a complex and multi-disciplinary endeavor, requiring the development and execution of modeling and optimization schema to provide decision-support.

In addition to these aspects of SWM systems, the development of such modeling and optimization tools is challenged by the significant variation in the configuration of SWM systems in Florida. In several highly-populated counties, the SWM system features a monolithic configuration, in which a strong public or private utility owns all or most resources used in the region. In the majority of counties, however, SWM systems feature a modular organization, in which numerous entities, both public and private, own the various facilities and fleets utilized. Many of these modular agents do not provide for the entire lifecycle of MSW treatment, and thus interaction and exchange amongst them is of vital importance. Each of these contractors is therefore a stakeholder to the SWM system, with a vested interest in its performance, but also with unique objectives and constraints that must be met for its continued business viability. Thus, a proposed solution must consider the many possible alternatives available in the study region, including various recycling programs, collection schemes, transfer arrangements, and disposal options, accurately assess and model the uncertainties facing each potential configuration of the SWM system, and provide a holistic analysis of the multi-faceted performance of each potential configuration.

In 2011, Antmann et al. [4] proposed a simulation-based decision-making and optimization framework for the analysis and development of effective solid waste management and recycling programs in monolithic systems. The framework was successfully applied in Miami-Dade County, Florida, which has the largest monolithic SWM system in the southeast United States. However, modular systems are used in much of Florida, and interact with monolithic systems. Therefore, in this project, we propose to develop a simulation and optimization framework capable of addressing both monolithic and modular SWM systems simultaneously, including interaction and exchange between and amongst such systems, in a mixed-topology, multi-county region. The proposed framework differs fundamentally from the formerly proposed approaches by replacing the discrete-event modeling topology with a novel multiple-objective, hybrid agent-discrete approach, and will be applied to the entire State of Florida, in order to capture the characteristics and dynamics of solid waste management in a broader and more comprehensive manner. Both the agent-based and discrete-event components of the proposed solution are compiled upon initialization, based on the contents of a standardized database, making the framework a general one, applicable to any real SWM system.

2. Proposed Methodology

Given the wide variation of scale, ownership structure, capacity, and facility inventory amongst the 67 county-level SWM systems in Florida, as well as the highly interdisciplinary nature of the performance analysis, a robust and adaptable framework is essential to accurately capture all potential system configurations. Along these lines, a framework consisting of three components has been developed in order to simulate and optimize the wide variety of SWM systems in use statewide. These components include a database, an assessment module, and a resource allocation optimization module. Figure 1 provides an overview of this framework.

2.1 Database

A structured database is built in this work to store the parameters of the 302 extant SWM facilities in the State of Florida. Information includes the location, owner, capacity, operating cost, greenhouse gas emissions, and recycling rate of each facility, as well as its current linkages to other facilities, in the case of transfer stations. The collection of this data presented substantial challenges in and of itself, due to the wide variance of reporting standards and operating schedules utilized statewide. These challenges were addressed by an in-depth data collection phase, which included the review of over 500 documents from regulators, public and private utilities, and other entities. All data was the converted to a standardized reporting format developed for the project, in which all facilities operate daily from 8:00 AM to 6:00 PM, 365 days annually. The structured database also addresses generation units, which were defined at the municipal level. Daily generation calculated by multiplying municipal population by the average per-capita waste generation rate for each respective county. The inventory of municipalities is based on data from the United States Census Bureau [5], and includes a total of 476 generation units. Each generation unit and processing facility was also assigned a unique identifying number at this stage, to provide a uniform reference and addressing mechanism for the other modules.

Primary objectives of the design and implementation of the database module are to provide a standardized format through which any facility or generation unit present in the real system can be accurately encoded, and to promote
ease of revision amongst end users. To these ends, SQL was selected as the database format, so that both programmatic access (for use by the model) and a graphical user interface (for ease of revision) are provided. Both descriptive characteristics of each agent (name, location, capacity or generation rate, fees, etc.) and the linkages extant in the real system (up to four per agent) are included in the database. A limit of four linkages per agent is set as it captures all configurations presently in use in the real system. The contents of the database are prepared before the initiation of experiments, and remained static throughout. However, due to the use of human-readable data formats, the database is easily editable for future venues. Information is read from the database each time the framework is initialized, so that updates made are included in the assessment and resource allocation optimization modules without modification.

![Figure 1: Proposed simulation-based decision-making framework for integrated solid waste management systems](image)

2.2 Assessment Module
The assessment begins by prompting the user to define an arbitrary study region, by selecting one or more counties from a graphical user form. Once a study region is defined, the assessment module then polls the database for the processing facilities and generation units located within the selected region, which are uploaded into the assessment module. The assessment module then converts the human-readable data in the database into a parameterized format, for use by constructors in the resource allocation optimization module while compiling the model. By running the assessment module each time the model is initialized, the latest database contents are always utilized, thus facilitating updating by end users and contributing to the overall generality of the system: inserting data from a different SWM system into the structured database will adapt the entire model to this system.

An advanced linking mechanism is provided in the assessment module, in order to establish linkages between the agents. Each generation unit and transfer node is provided with four linkages: two for recyclables and two for
wastes. The linkages contain two values: the unique facility identifying number of the appropriate delivery node, as assigned by the database, and the proportion of total arrivals to be delivered to this node. Both values are populated based on the database contents, and an error-checking mechanism ensures all delivery proportions sum to 100% for each agent. This linkage mechanism offers advantages over those found in the literature, by eliminating the need for binary or continuous variables to control the utilization of all possible linkages. In such systems, the number of linkage variables increases exponentially with the number of nodes, thus rapidly limiting the scalability of such a system under fixed computational resources. In contrast, in the proposed system the number of variables needed increases linearly with the number of nodes, allowing substantially larger systems to be modeled without excessive computational burden. The advanced linking mechanism is also utilized for the determination of inter-dependent counties. An inter-dependent county is defined as one which either transfers materials to, or receives materials from, one or more counties selected for the study region. Such arrangements exist in the real system when one or more counties in the study region do not have the necessary facilities to complete the SWM lifecycle for the entirety of their generation, or when such arrangements are economically advantageous. This is carried out during the polling of the structured database, by determining the county in which each delivery destination referenced in the linkages of the selected facilities is located, and including all such counties in the defined study region. The assessment module also polls all generation units and facilities not selected for inclusion after this step, and adds counties in which a generation unit or processing facility delivers waste to a node in the selected study region.

Due to the large scale of the SWM systems under review, especially in multi-county regions, the geographic relationship of various agents has a significant impact on the time required by, and costs incurred by, the transfer system. Therefore, an integrated Geographic Information System (GIS) is also included in the assessment module. The GIS uses road network information provided by the United States Census Bureau’s TIGER/Line system, combined with the location of each agent loaded by the database, to determine the road distance and travel time for all possible linkage arcs, whenever required by the model. This data is stored in a directory, which is referenced by the model upon utilization of the transfer mechanism to provide the real travel distance of each route. Thus, the impact of the geographical configuration of large-scale SWM systems is accurately captured by the model, and the impact of linkage configurations on transfer cost and time can also be simulated.

2.3 Resource Allocation Optimization Module
The resource allocation optimization module contains the hybrid agent-discrete model of SWM systems. Upon the initialization of the resource allocation optimization module, the parameterized data from the assessment module is fed to a collection of automated constructors, which compile the model on-demand. Constructors are provided for both the generation units and processing facilities, as well as for two classes of transfer agents: collection vehicles and transfer vehicles. The hybrid agent-discrete topology is achieved by compiling embedded discrete-event submodels with the facility and generation unit constructors. The relation between the agent-based model and the discrete event model is detailed in Figure 2.
The generation units and processing facilities are both included as agents in the agent-based model. At generation units, an inventory counter is maintained. Within the discrete submodel, it is incremented each morning at 8:00 AM by the daily generation rate obtained from the assessment module, and decremented as wastes are collected by the collection vehicle agents. In the discrete submodel provided for each facility, operational and cost counters are incremented in a discrete event with the arrival of each transfer vehicle. Updates to capacity, inventory, and cost counters made in the discrete submodels are recorded in the agent-based model in real time, so that reports can be generated detailing the economic and operational performance of each agent, and the performance analysis and feasibility verification components of the optimization mechanism may be implemented exclusively via the agent-based model. The collection and transfer vehicle agents link the generation and facility agents, based on the advanced linking mechanism prepared in the assessment module. These transfer agents decrement their capacity from the generation unit’s inventory, and then select a delivery destination based on the linkage existed between the generation units and the processing facilities. This mechanism also addresses the uncertainties present in the real system relating to the exact distribution of deliveries on a given day, through the use of a random distribution to select a destination based on the probability of each of the four linkages present in the “smart-linking” system. Once a destination is decided, the truck is dispatched, and global mileage counters are incremented based on the mileage provided by the GIS directory prepared in the assessment module. Upon arrival at a processing facility, wastes are submitted to the discrete submodel for processing and the updating of the various operational counters. Transfer vehicles are assigned to transfer stations in the same manner as the collection vehicles, and operate in the same manner once dispatched. Formulation of the waste allocation embedded in the hybrid agent-discrete model is detailed in the next section.

3. Formulation of the Multi-objective Waste Allocation Problem

The proposed decision making framework allows stakeholders to optimize overall interests or the interests of each agent, in terms of minimizing total cost and maximizing environmental benefits (maximum recycling rate and minimum emissions) that occur throughout the entire SWM lifecycle. In order to keep the consistency of the formulation throughout this section, we briefly provide the notation first in the table provided below.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
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<tbody>
<tr>
<td>$i$</td>
<td>County</td>
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<tr>
<td>$j$</td>
<td>City</td>
</tr>
<tr>
<td>$t$</td>
<td>Transfer station</td>
</tr>
<tr>
<td>$r$</td>
<td>Material recovery facility</td>
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<tr>
<td>$w$</td>
<td>Waste-to-energy plant</td>
</tr>
<tr>
<td>$l$</td>
<td>Landfill</td>
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<tr>
<td>$f$</td>
<td>Emission rate</td>
</tr>
<tr>
<td>$M$</td>
<td>Number of Counties</td>
</tr>
<tr>
<td>$N_i$</td>
<td>Number of cities in county $i$</td>
</tr>
<tr>
<td>$T_i$</td>
<td>Number of transfer stations in county $i$</td>
</tr>
<tr>
<td>$R_i$</td>
<td>Number of material recovery facilities in county $i$</td>
</tr>
<tr>
<td>$W_i$</td>
<td>Number of waste-to-energy plants in county $i$</td>
</tr>
<tr>
<td>$L_i$</td>
<td>Number of landfills in county $i$</td>
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<tr>
<td>$T$</td>
<td>Time horizon</td>
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</table>

In our formulation of the problem, the total daily waste collected in county $i$ is represented by $W_i$. The daily waste processed in different types of facilities (transfer station, MRF, WTE, and landfill) in county $i$ are denoted as $Q_i^t$, $Q_i^r$, $Q_i^w$ and $Q_i^l$, respectively. We introduce the decision variables $x_{jt}$, $x_{jr}$, $x_{jw}$, $x_{jl}$ to denote the amount of waste transferred from city $j$ to transfer station $t$, material recovery facility $r$, waste-to-energy plant $w$ and landfill $l$ in county $i$ per day; and decision variables $x_{tr}$, $x_{tw}$, $x_{tl}$ to denote the amount of waste transferred from transfer station $t$ to MRF $r$, WTE $w$ and landfill $l$ in county $i$ per day, respectively. In order to capture the relationships among the city governments and private companies which illustrate the permission for the waste processing and disposal, binary variables representing if the contracts existed among the cities and companies are added in the optimization model. The detailed explanations of these variables are provided through Eq. (1)-(7).

\[
y_{jt} = \begin{cases} 1, & \text{if city } j \text{ and transfer station } t \text{ have contracts} \\ 0, & \text{otherwise} \end{cases} \tag{1}
\]

\[
y_{jr} = \begin{cases} 1, & \text{if city } i \text{ and material recovery facility } r \text{ have contracts} \\ 0, & \text{otherwise} \end{cases} \tag{2}
\]
Given the parameters and decision variables, the multi-objective waste allocation problem is formulated with the following objectives: 1) the cost objective is defined as the minimization of the total costs ($TC_i$) for solid waste management in county $i$, including the construction cost ($CC_i$), transportation cost ($CT_i$), facility operating cost ($CP_i$); 2) the environmental objective is to minimize the total emissions ($E_i$), which are calculated based on the amount of gases generated per ton of wastes processed at waste-to-energy plants and landfills; 3) the recycling goal is considered as maximizing the recycling rate ($RR_i$) throughout the waste transfer-process flow. Detailed formulations of the three objectives are given in Eq. (8)-(13).

$$Z_i = \text{Min } TC_i = CC_i + (CT_i + CP_i), \forall i,$$  

$$CT_i = \sum_{j=1}^{N_j} \sum_{r=1}^{N_r} d_{ij} x_{ij} y_{ij} + \sum_{j=1}^{N_j} \sum_{r=1}^{N_r} d_{jr} y_{jr} + \sum_{j=1}^{N_j} \sum_{w=1}^{N_w} d_{jw} y_{jw} + \sum_{j=1}^{N_j} \sum_{l=1}^{N_l} d_{jl} y_{jl}, \forall i,$$  

$$CP_i = \sum_{r=1}^{N_r} p_i^{\text{ref}} Q_i^{\text{ref}} + \sum_{r=1}^{N_r} p_i^{\text{ref}} Q_i^{\text{ref}} + \sum_{r=1}^{N_r} p_i^{\text{ref}} Q_i^{\text{ref}} + \sum_{r=1}^{N_r} p_i^{\text{ref}} Q_i^{\text{ref}} + \sum_{r=1}^{N_r} p_i^{\text{ref}} Q_i^{\text{ref}} + \sum_{r=1}^{N_r} p_i^{\text{ref}} Q_i^{\text{ref}}, \forall i,$$  

$$Z_3 = \text{Max } RR_i = \frac{\sum_i q_i}{\sum_i q_i + \sum_i q_i + \sum_i q_i + \sum_i q_i + \sum_i q_i}, \forall i.$$  

Here, $t$ represents the transportation cost per ton per mile, $C_i$ is the construction cost of facility ($t, r, w, l$) in county $i$, $P_i$ represents the processing cost of facility ($t, r, w, l$) in county $i$, $d_{ij}^{rt}, d_{jr}^{rt}, d_{jw}^{rt}, d_{jl}^{rt}$ denote the distance between city $j$ and facility ($t, r, w, l$) in county $i$, and $d_{tr}, d_{tw}, d_{tl}$ denote the distance between transfer station $t$ and other facility ($t, r, w, l$) in county $i$, respectively.

Eq. (14) demonstrates that the daily waste transferred into the facility cannot exceed the maximum capacity of that facility, in which $Cap_i^{\text{ref}}$ represents the maximum daily capacity of facility ($t, r, w, l$) for county $i$. Eqs. (15)-(19) are the mass balance equations, and the Eqs. (20)-(22) illustrate the restriction that the summation of the recycling rate and the disposal rate should be 100%, in which $n_i^2$ is the percentage of recycled wastes in city $j$, $n_i^2$ is the percentage of disposed wastes in city $j$, $n_i^2$ represents the percentage of wastes transferred for recycling in transfer station $t$, and $n_i^2$ denotes the percentage of wastes transferred for disposal in transfer station $t$, respectively.
The candidate solution set consists of different combinations of these linkage values, and the performance of each candidate is evaluated via the performance-monitoring variables included in the agent constructors and the agent-specific objective functions embedded in the system. Figure 4 presents the operations of optimization module.

4. Experiments and Results
A series of experiments were designed and carried out on the proposed framework, utilizing the existing SWM infrastructure in Florida as the case study. Experiments were carried out both at the county level during one month operation and in multi-country regions, as defined by the FDEP, over an eight-year period from 2012 to 2020. Waste generation rates were held constant throughout this period, due to a dearth of consensus data on population and waste generation growth, and the inventory of SWM facilities was also held constant, due to the extended timeframe required to cite, design, permit, and construct such facilities.

For the county-level experiments, the optimization was carried out with two objective functions: maximize recycling and minimize cost. Duval and Hillsborough Counties were selected, representative of two near-extremes of scale and complexity encountered in the state. Duval County has a relatively simple modularized SWM system, in which five generation units, five processing facilities, and one transfer station serve a population of 866,000. This county was selected to test the performance of the proposed framework on simple modularized systems, and determine the range of feasible results produced. Hillsborough County has a markedly more complex modularized SWM system, in which 13 processing facilities and 5 transfer stations serve 1.2 million residents in 4 generation units in the Tampa area. This county was selected to evaluate the performance of the framework both in more complex modular systems and under heavy transfer station utilization. Furthermore, Hillsborough County was selected to determine
the scalability of the framework to complex single-county systems, in terms of computational burden and the range of feasible cost-recycling rate solutions identified. Figures 4(L) details the results from the Duval County experiments and Figure 4(R) presents the results from Hillsborough County.

Data from the Duval County experiments exhibited both a greater number of feasible solutions and a greater range of recycling rates and costs in the feasible solutions than data from Hillsborough County, provided the same number of iterations (10,000 for each county). The former trend indicates that computational demand clearly rose with system complexity. However, the range of costs and recycling rates identified in the Hillsborough County experiments was greater than that in the Duval County experiments. Unlike the number of solutions, the range of feasible solutions depends heavily on the configuration of the real system in addition to the optimization mechanism. Therefore, the range of the results cannot be used as an indicator of the scalability of the modeling protocol or optimization mechanism from these two counties alone, and the difference in the range of results instead indicates that the proposed framework identified the divergent characteristics of the two systems. Despite the inconsistency in the range of solutions, in both counties the framework identified candidate solutions with greater recycling rates than presently achieved. This indicates the fitness of the model and optimization tools in evaluating all potential configurations of the real SWM system. The points on the cost-recycling rate plot form a clear Pareto boundary, suggesting that a maximum performance curve was identified. Thus, the generation of feasible results with recycling and cost performance greater than present renders these experiments a success.

For the region-level experiments, the FDEP’s southeast region was selected. This region includes the densely-populated Tri-County area of Miami-Dade, Broward, and Palm Beach counties, as well as several surrounding counties, and was selected due to the high level of complexity, numerous facility agents (69), and many generation units (125) present. Table 2 provides the details for the generation units and facilities in the region. Two recycling rate statistics were reported, the “recycling rate,” defined as the tonnage delivered to MRF facilities divided by the total tonnage of MSW generated, and the “adjusted recycling rate,” defined as the former except modified pursuant to Florida State Statutes (FSS) Chapter 403.706 [6], by which: (1) one ton is credited to the recycling total per megawatt-hour (MWh) of net electrical generation at waste-to-energy (WTE) facilities, and (2) in counties in which over 50% of MSW generation is combusted in-county, the credits to the recycling total are doubled.

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<table>
<thead>
<tr>
<th>Table 2: Agent Information for Southeast Region</th>
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<td><strong>Facilities</strong></td>
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<td>Landfill</td>
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Figures 4: Results from Duval County (L) and Hillsborough County (R) experiments under both objective functions.
Like the county-level experiments, none of the candidate solutions generated during these experiments yielded a 75% recycling rate or adjusted recycling rate. Given the success of the framework in identifying candidates with greater recycling performance than presently achieved, this indicates that the existing infrastructure in this region lacks the capacity to achieve this goal. It should also be noted that, as illustrated in Table 2, total MRF capacity in this region exceeds 75% of total waste generation. Therefore, all MRF capacity is clearly not being utilized, either at present or by any of the candidate solutions found, and the first recommended actions would be to better utilize this capacity. Low utilization of these resources may either be due to either ineffective diversion and collection programs, in which case an insufficient volume of dual or single-stream recyclables is available to be allocated to these MRF facilities by the framework, or due to the contractual environment, in which case the linkages between MRF capacity and generation units may be sub-optimal. Although the proposed framework is unable to determine which is the case, in either scenario, the most cost-effective means of increasing recycling performance would be to better utilize these facilities.

Despite this shortcoming, experiments yielded adjusted recycling rates significantly greater than current performance, which is approximately 10%. The significant disparity between the adjusted and unadjusted recycling rate indicates that this gain was achieved largely with WTE facilities. Therefore, for this region, the framework identified the most cost-effective means of achieving the 75% adjusted recycling rate as an increase WTE capacity, given the system’s present inability to fully utilize existing MRF capacity. For the case of Florida, once WTE usage reaches 50% of total disposal, the recycling credits from electrical generation are doubled, as per FSS 403.706, further supporting this finding of the framework. Furthermore, adding WTE capacity eliminates the impact of the strength of the market for recycled materials, which is widely variable and strongly elastic, and potential public resistance to modified collection and billing structures necessary to achieve greater diversion rates.

5. Discussion and Conclusions
In this paper, a multi-objective hybrid simulation and optimization framework for integrated solid waste management systems is proposed, in which agent-based modeling and discrete-event modeling techniques are combined to form a novel hybrid agent-discrete modeling framework. The proposed framework advances upon earlier models in the SWM field by simulating and optimizing both monolithic and modular SWM systems singlehandedly and simultaneously. Such capability makes it applicable both to more SWM systems and to larger regions, in which systems of both topologies interact. Furthermore, an advanced linking mechanism provides superior performance and reduced memory utilization compared with earlier linkage systems controlled by arrays of binary or continuous variables. Under the proposed linking mechanism, variables are only established for those
linkages which are utilized by a given candidate solution, regardless of how many possible linkage arcs are available in the study region. Therefore, the scalability of modeling framework given typical computation resources ceases to limit the scale of study regions. Through the use of automated agent constructors, the framework can be prepared and stored in a general form, so that when initialized, the compiled model reflects the latest contents of the structured database and arbitrary study region defined by the user. Thus, by altering the contents of the structured database and GIS road data, the model is perfectly applicable to any SWM system utilizing the types of facilities present in the State of Florida. Uncertainties at the system and facility levels were considered by the framework, and performance of each agent is recorded in terms of operational, economic, and environmental perspectives via the real-time processing simulation embedded in the agent-based component. The discrete submodels provided allow intrinsically discrete processes, such as the arrival and dispatch of transfer vehicles, to be modeled as such, while retaining the performance and scalability of an overall agent-based modeling approach. Furthermore, due to the independence of these submodels, simultaneous events at independent facilities are accurately captured, unlike under global discrete-event modeling tools.

A series of experiments were carried out using the existing SWM infrastructure in the State of Florida, through which the feasibility and effectiveness of the proposed framework is successfully demonstrated. The solutions generated both improve upon the current performance of the real-world systems and reflect the marked differences in the dynamics of the various county and region-level SWM systems reviewed, through the range of solutions generated for each system and the facility types utilized. The primary limitation of the proposed framework is the exclusion of diversion and collection processes from its analysis. Therefore, a complete lifecycle analysis of SWM infrastructure is not provided, and the source-separation of recyclables is not captured. Due to this shortcoming, the volume of materials deliverable to MRF or other recycling facilities is not simulated, and thus held constant from the real system at initialization. Furthermore, a significant portion of the total cost is incurred during transportation in this segment, which may impact the performance of the optimization mechanism and the nature of the most optimal solutions found. Consideration of diversion and collection process is a future venue of this work, and requires scope extension of the modeling and additional computational resources. Furthermore, given the inability of the existing infrastructure to achieve the 75% recycling goal by 2020, the future venues of this work include strategic planning of capital projects, including facility expansion and new construction, optimization of the fleet size, and analysis of the participation rates of recycling programs. In order to increase the accuracy of the results and reduce the computational burden associated with the resultant vast solution space, an advanced optimization algorithm is also a future venue of this work. A broader variety of applications and more precise results would be provided by the consideration of these segments.

References