A Decision-Support Simulation Platform for Evaluating Construction and Demolition Debris Recycling Policies in Florida Counties

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Abstract

Florida generates millions of tons of construction and demolition (C&D) debris annually, yet recycling performance varies widely across counties and is often limited by economic and infrastructure constraints. Despite documented economic and environmental benefits of C&D recycling, most Florida counties operate without a diversion ordinance. County officials seeking to improve C&D recycling rates face a fundamental problem: they lack the analytical tools to evaluate how alternative policy designs, diversion mandates, deposit-refund systems, differential tipping fees, facility certification standards, procurement mandates for recycled materials, or combinations thereof, would perform under their specific local conditions before committing public resources and political capital to implementation.

This project develops a decision-support simulation prototype designed to give county solid waste managers, planners, elected officials, and recycling industry stakeholders a practical means of testing C&D recycling policy options before adopting them. The prototype models the key actors in the C&D waste system (i.e., contractors of different firm sizes making material-by-material disposal decisions, recycling facilities with specific processing capacities and gate policies, landfills, end-product markets, and regulatory bodies) and captures how these actors interact and respond when policy conditions change. The model accounts for the factors that drive disposal decisions in practice such as cost, convenience, compliance pressure, risk tolerance, and the reality that a large demolition firm with established recycling relationships will respond to a new ordinance very differently than a small contractor accustomed to landfilling.

The research is carried out in four phases. The first documents the current regulatory environment, fee structures, facility characteristics, and contractor practices across Florida counties. The second translates these findings into a structured model of how stakeholders make decisions, how materials flow through the system, and where policy interventions take effect. The third builds and validates the simulation, calibrating it against observed diversion rates in a representative Florida county with different policy environments and facility infrastructure. The fourth applies the validated prototype to test various policy architectures. Each scenario is tested under county-specific conditions to determine not only whether a policy improves diversion, but by how much, at what cost, with what impact on different sizes of contracting firms, and with what unintended consequences including illegal dumping, processing bottlenecks at recycling facilities, material leakage to neighboring counties, and market saturation of recycled products.

This prototype is designed from the outset to demonstrate a practitioner-operated tool, developed and tested for a single Florida county as a proof of concept. County staff can input their own local parameters (e.g., tipping fees, facility locations, contractor populations, hauling distances, and current diversion rates) and receive outputs that directly inform policy decisions: projected diversion rates with confidence intervals, compliance costs broken down by contractor

firm size, facility utilization and bottleneck risk, enforcement staffing requirements, net fiscal impact to the county, and environmental benefits including estimated greenhouse gas reductions.

1 Introduction and literature review

C&D waste management is a critical issue globally, accounting for more than 30% of total waste worldwide [1], [2]. The environmental impacts of C&D waste cause serious air, water, and land pollution [3]. A large amount of C&D debris goes unrecycled due to economic factors, reluctance of potential end markets to change practices, and environmental concerns regarding recycling alternatives [4]. Furthermore, most C&D recycling facilities operate at only 70–75% of their potential throughput because of contamination, market limitations, and variability in local regulatory requirements [5]. The lack of a supportive regulatory framework, and the complexity of policy establishment pose challenges [6], particularly given the significant variation documented across counties in permitting practices, reporting requirements, and institutional oversight [7], [8]. Additionally, the economic viability of C&D waste recycling often faces challenges, with underdeveloped markets for recycled materials and a reluctance among potential end-users to change existing practices [9]. To mitigate these challenges, it is essential to systematically evaluate the regulatory instruments, economic incentives, and institutional mechanisms that govern C&D waste management [2], [6].

A growing body of literature has examined the types and effectiveness of policy instruments available to governments seeking to improve C&D recycling outcomes [10], [11], [12]. Studies have categorized these instruments into three broad groups: command-and-control measures such as mandates, disposal bans, and sorting requirements; market-based mechanisms including landfill taxes, differential tipping fees, and subsidies; and information-based tools such as green product labeling, technical standards, and stakeholder education [13]. Reviews of U.S. state-level regulations have revealed highly inconsistent regulatory frameworks, with only a minority of states maintaining specific C&D landfill or recycling facility regulations, and landfilling continuing to dominate despite growing awareness of recycling opportunities [14]. Longitudinal evaluations of construction waste management policies have demonstrated that pricing-based instruments, such as landfill charging schemes can produce significant initial reductions but may lose effectiveness over time without complementary enforcement and infrastructure development [15]. Broader comparative studies contrasting developed and developing economies have found that recycling performance depends heavily on the maturity of legal frameworks, the availability of processing infrastructure, and the strength of enforcement mechanisms [16], [17]. Policy reviews have identified a wide range of potential measures, from pre-demolition audits and selective demolition mandates to extended producer responsibility and green public procurement, and have emphasized that combining regulatory, economic, and informational tools into integrated policy packages yield stronger outcomes than any single instrument deployed in isolation [18]. A consistent finding across these studies is that policies targeting market demand for recycled materials, including procurement mandates, quality certification systems, and environmental labeling, are critical for sustaining recycling gains, as supply-side measures alone are insufficient without corresponding demand-side support [17].

Complementing these policy analyses, a parallel line of research has employed quantitative modeling and simulation methods to evaluate the economic viability and system-level effects of specific C&D recycling strategies. Economic feasibility studies have demonstrated that recycling facilities often struggle to achieve profitability under current market conditions, particularly in regions where virgin materials are abundant and inexpensive, underscoring the importance of

policy interventions that alter the cost structure in favor of recycling [19]. Computer simulation models have been used to simulate the long-term effects of subsidy and environmental tax combinations, revealing that combined incentive policies outperform single-instrument approaches and that optimal incentive levels exist beyond which diminishing returns or unintended consequences, such as increased illegal dumping, may emerge [20], [21]. Moreover, studying the interactions among government, building material enterprises, and waste recycling enterprises, shows that differentiated subsidies tailored to enterprise capability and consumer quality perception are more efficient than uniform subsidy schemes, and that improving consumer confidence in recycled materials can partially substitute for direct financial incentives [22], [23]. Optimization-based decision-support frameworks incorporating regional socio-economic and regulatory factors have shown that material recovery feasibility is highly context-dependent, with regulations and cultural norms exerting greater influence than labor costs alone, reinforcing the need for regionally tailored strategies rather than universal solutions [24], [25]. Integrated approaches combining stakeholder engagement, lifecycle analysis, and circular economy principles have identified logistics costs and on-site operational inefficiencies as primary practical barriers, advocating for smart dismantling practices, advanced sorting technologies, and closed-loop supply chain development as essential complements to policy action [26].

Although prior research has advanced understanding of C&D waste generation and material flows, several important limitations remain. Much of the existing literature emphasizes quantifying waste streams or modeling processing technologies, while giving comparatively less attention to the broader economic and regulatory structures that shape decisions across the supply chain [10] [27]. Moreover, most existing studies focused on regulatory structures, evaluate policy instruments in isolation rather than modeling how multiple instruments interact when deployed simultaneously within a system of interdependent actors. As a result, the cumulative economic and environmental implications of contractor behavior, facility operations, and policy design are not fully captured. Research examining social dimensions, such as contractor attitudes toward compliance requirements, or public acceptance of recycled materials, also remains limited, despite their relevance to diversion outcomes. Moreover, relatively few empirical studies have evaluated and produced causal evidence of the effectiveness of specific regulatory tools, including diversion ordinances, deposit-refund mechanisms, or fee and surcharge structures, even though these instruments increasingly influence C&D management in U.S. jurisdictions. These gaps point to the need for research that adopts a holistic perspective on the C&D waste system, integrating regulatory, economic, environmental, and behavioral considerations to assess how different policies influence system-wide performance [28], [29].

2 Methodology

2.1 Research Design Overview

The proposed research follows a four-phase approach consisting of three core development stages, definition, abstraction, and implementation, followed by a final phase focused on scenario analysis (Figure 1). In the definition phase, we engage with stakeholders and review existing literature and practices to identify key actors, decision points, and system boundaries within the C&D waste recycling ecosystem. The abstraction phase translates this real-world understanding into a conceptual SoS architecture, defining the main systems, agent behaviors, and interaction pathways. In the implementation phase, this architecture is brought to life using a hybrid simulation model.

The simulation integrates three complementary modeling methods, each addressing a distinct analytical need that the others cannot fulfill. (1) Agent-based modeling (ABM) represents the decision-making of individual actors, contractors, facility operators, and market participants, each with unique characteristics and behavioral rules. This is essential because contractors are not homogeneous: a large commercial demolition firm with established recycling relationships will respond to a policy differently than a small residential contractor accustomed to landfilling [30], [31]. (2) Discrete-event simulation (DES) represents the physical flow of material through the system, trucks hauling loads, queues forming at facility gates, loads being inspected and accepted or rejected, material being processed into output products. This operational layer determines whether the physical infrastructure can handle the material volumes that a policy redirects toward it [32]. (3) System dynamics (SD) represents the slower forces that evolve over months and years: market prices for recycled products, facility investment in new capacity and quality, and the gradual changes in contractor behavior as they learn and adapt to new policy conditions [30]. The integrated model will be validated through a multi-stage protocol that includes face validation of the conceptual model by industry practitioners and county solid waste officials, calibration against observed diversion rates and material flow data from a single representative Florida county, and systematic sensitivity analysis to identify the parameters most influential on model outputs.

In the final phase, the validated simulation is used to test specific policy scenarios that represent the range of options realistically available to the selected representative Florida county. Examples of such policies include a diversion ordinance, an economic incentive package combining tipping fee restructuring with a deposit-refund system linked to the building permit process, a demand-side intervention pairing a county procurement mandate for recycled aggregate with a facility certification program, a self-financing surcharge fund in which a per-ton charge on landfill disposal funds recycling infrastructure improvements, and material-specific landfill bans enforced at the facility gate.

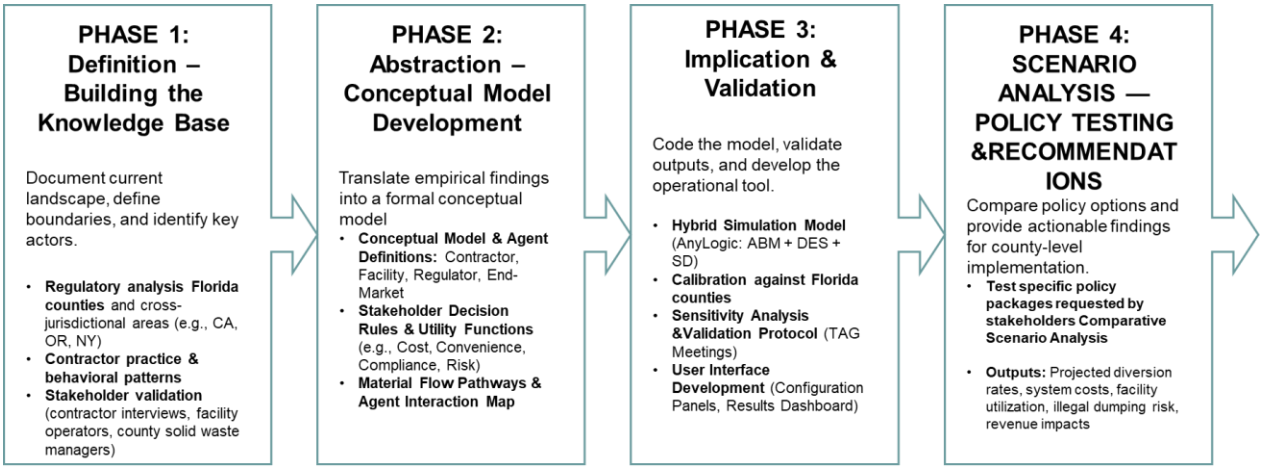

Figure 1. Four phase methodology to study Construction and Demolition Debris Recycling Policies

Why is the simulation model needed?

A central question motivating this research is why a simulation prototype is necessary when the directional effects of most C&D recycling policies are well understood. It is broadly recognized that diversion mandates increase recycling rates, that higher landfill fees shift material toward recycling facilities, and that deposit systems create compliance incentives. However, the directional effect of a policy is not the information that county officials require to make sound

implementation decisions. What they require, and what is currently unavailable to them, is the quantified performance of a specific policy design under their county's specific conditions, including its magnitude, its cost, its distributional consequences, and its unintended side effects. The proposed framework is designed to provide precisely this information.

Consider the distinction between knowing that a mandate increases recycling and knowing by how much it increases recycling in a county with a specific number of MRFs, a specific volume of active construction and demolition permits, and a specific contractor population profile. Lee County's 50% diversion ordinance has produced a 97% recycling rate, far exceeding the mandated threshold. However, Lee County's result reflects a particular combination of facility infrastructure, contractor relationships, and enforcement capacity that other counties do not necessarily share. A county with fewer processing facilities, longer haul distances, or a contractor population composed predominantly of small firms will produce a substantially different outcome. The simulation generates county-specific projections with confidence intervals. For example, that a 50% ordinance in a given county would yield a projected diversion rate of 47–58% with 80% probability, would require 1.0 FTE of enforcement capacity at an annual cost of approximately $85,000, would generate $120,000–$180,000 in diversion fee revenue, and would increase MRF utilization from 55% to 78% of permitted capacity. This level of specificity is what distinguishes an actionable policy recommendation from a general principle, and it cannot be derived from qualitative reasoning alone.

More importantly, every C&D recycling policy produces secondary and tertiary effects that are not visible through analysis of any single actor or policy instrument in isolation. Such behaviors emerge from interactions among various parties involved and cannot be predicted by analyzing any single actor in isolation. The simulation is specifically designed to identify and quantify various emergent behaviors that are most relevant for policy design. Examples of such behaviors are provided as follows:

(1) Illegal dumping: when a county increases landfill tipping fees to create a price incentive for recycling, a portion of the contractor population will redirect material to recycling facilities as intended. However, for contractors operating on narrow margins the fee increase raises the cost of all legal disposal options simultaneously. If the expected cost of illegal disposal (the probability of detection multiplied by the applicable fine) remains below the increased cost of legal alternatives, some contractors will shift material to unauthorized sites. Illegal dumping is consistently identified as the most significant concern when county commissions evaluate C&D recycling policies. The simulation models illegal disposal as an explicit pathway in every contractor agent's decision function. This enables the prototype to identify the specific fee level at which illegal dumping incidence begins to increase, and the specific enforcement intensity, expressed as audit probability and penalty magnitude, required to maintain dumping rates at or below baseline.

(2) Facility bottleneck cascades: when a mandate or fee structure redirects significant material volume from landfills to MRFs, the receiving facilities must possess sufficient processing capacity to absorb the additional throughput. Where capacity is insufficient, processing queues develop, wait times at the gate increase, and the effective cost of recycling rises. If wait times become sufficiently prolonged, contractors begin routing loads back to landfills or to less congested facilities in neighboring jurisdictions, partially or fully offsetting the policy's intended diversion effect. The simulation tracks facility queues, processing times, and utilization rates explicitly, and can identify the threshold at which a given policy's material redirection exceeds the

county's available processing capacity before the policy is enacted, rather than after implementation reveals the constraint.

(3) cross-county policy leakage: when a single county adopts fee increases or regulatory requirements that neighboring counties have not adopted, contractors whose project sites are located near county boundaries may route material to lower-cost facilities in adjacent jurisdictions. The implementing county observes a decline in landfill tonnage and may interpret this as evidence of increased recycling, but if the diverted material has simply crossed a county boundary to reach a cheaper landfill, no net diversion has occurred. The magnitude of this leakage effect depends on the specific spatial configuration of facilities, the fee differential between jurisdictions, and the additional hauling distance contractors must accept. Because the simulation includes all permitted C&D facilities within a 30-mile radius of each county regardless of jurisdictional boundaries, it captures cross-county routing endogenously and reports the net system-level diversion rate rather than the apparent within-county effect.

(4) Market saturation and price depression: when a policy significantly increases the volume of recycled C&D products entering the market without a corresponding increase in demand, the market price for those products declines. In Florida, where recycled aggregate competes with abundant and inexpensive virgin limestone, even a moderate price decline can push the recycled product below facility operating cost, rendering recycling economically unviable despite the policy support. A mandate intended to increase recycling can, through this market mechanism, undermine the financial viability of the very facilities it was designed to benefit. The simulation's market dynamics model tracks supply, demand, and price for each recycled product type and identifies the supply volume at which price depression threatens facility viability — directly informing the design decision of whether to pair supply-side mandates with demand-side interventions such as procurement requirements.

Finally, the simulation addresses a dimension of particular importance for political feasibility: the distribution of compliance costs across the contractor population. A policy that increases the county's average diversion rate by a meaningful margin may concentrate the majority of its compliance burden on small contractors who lack the equipment, staffing, and facility relationships needed to sort and route material efficiently. A large demolition firm with a dedicated waste management coordinator and established accounts at multiple recycling facilities may comply with a new ordinance at modest incremental cost, while a small residential renovation contractor may face a substantial increase in time, documentation requirements, and per-project expense. County commissions considering diversion ordinances routinely receive testimony from small contractor associations asserting that proposed regulations will impose disproportionate hardship. Without quantified distributional data, the commission cannot evaluate these claims. The simulation models contractors of different firm sizes with distinct behavioral parameters and reports compliance cost impacts by size category, enabling the commission to assess whether disproportionate burden exists and, if so, to design accommodations (e.g., exemption thresholds for projects below a specified value, graduated phase-in schedules, or simplified documentation requirements for small projects) that mitigate the burden without compromising the policy's effectiveness.

2.2 Phase 1: Definition: Building the Knowledge Base

The definition phase establishes the foundation upon which the entire simulation rests. It documents three categories of information through parallel tasks: the regulatory and economic

landscape across Florida's counties, the behavioral patterns of the sector's key actors, and the physical characteristics of the material flow system.

Regulatory and Policy Landscape
This task documents the regulatory environment, fee structures, and facility infrastructure across Florida's counties to establish the empirical foundation on which the simulation's county-specific projections depend. The simulation cannot produce meaningful results for a given county without accurate local parameters. For each county, the following is documented through systematic review of county ordinance codes, FDEP solid waste annual reports, facility permit records, and published fee schedules: the presence and design of any diversion requirement, permit-linked obligations such as waste management plans and compliance reporting, fee structures at county-operated and private facilities, penalty and enforcement mechanisms, and facility certification or approval requirements. The PI team has already compiled detailed profiles for several Florida counties as well as a comparison database of 42 jurisdictions across California, Oregon, and New York with established C&D ordinances, providing both a head start on the Florida data collection and a cross-jurisdictional reference for policy design options that have been tested elsewhere.

Stakeholder Validation
The simulation's agent decision models are built from established research on contractors, facility operators, and market behavior (described in Phase 2 below). However, these literature-based models must be validated and calibrated against Florida-specific practice. Focused validation interviews will be conducted with demolition and general contractors across Florida counties, 8C&D recycling facility operators, and county solid waste managers. These interviews are structured around the model's specific parameters: the investigator presents the default values derived from the literature, and the practitioner confirms, adjusts, or flags them for local conditions. The county manager interviews serve an additional purpose: identifying the specific policy questions that each county wants the simulation to answer, ensuring the scenario analysis in Phase 4 addresses real decision-making needs.

Material Flow and Facility Characterization
This task quantifies the physical system the simulation must represent. C&D generation rates by project type (new residential construction, commercial construction, residential and commercial demolition, renovation) and by county are compiled from FDEP annual reports and county waste characterization studies. Facility locations and permitted capacities are geo-referenced using FDEP permit records, including facilities in neighboring counties within a 30-mile haul radius. Including cross-county facilities is essential for realistic modeling: when a county raises tipping fees or tightens diversion requirements, contractors routinely route loads to cheaper facilities in adjacent jurisdictions, and the simulation must capture this leakage effect to avoid overstating the impact of county-level policies. The output of this task is a geo-referenced facility database and a set of county-specific material flow profiles that serve as initial conditions for the simulation.

2.3 Phase 2: Abstraction: Conceptual Model Development

The abstraction phase translates the empirical findings from Phase 1 into a formal conceptual model (Figure 2) that serves as the blueprint for the computational simulation. The conceptual model defines four agent types (contractor, facility, regulator, and end-market), specifies their

decision rules, and maps the interactions among them. The following sections describe each agent, the market dynamics, and the emergent system-level behaviors the simulation is designed to capture.

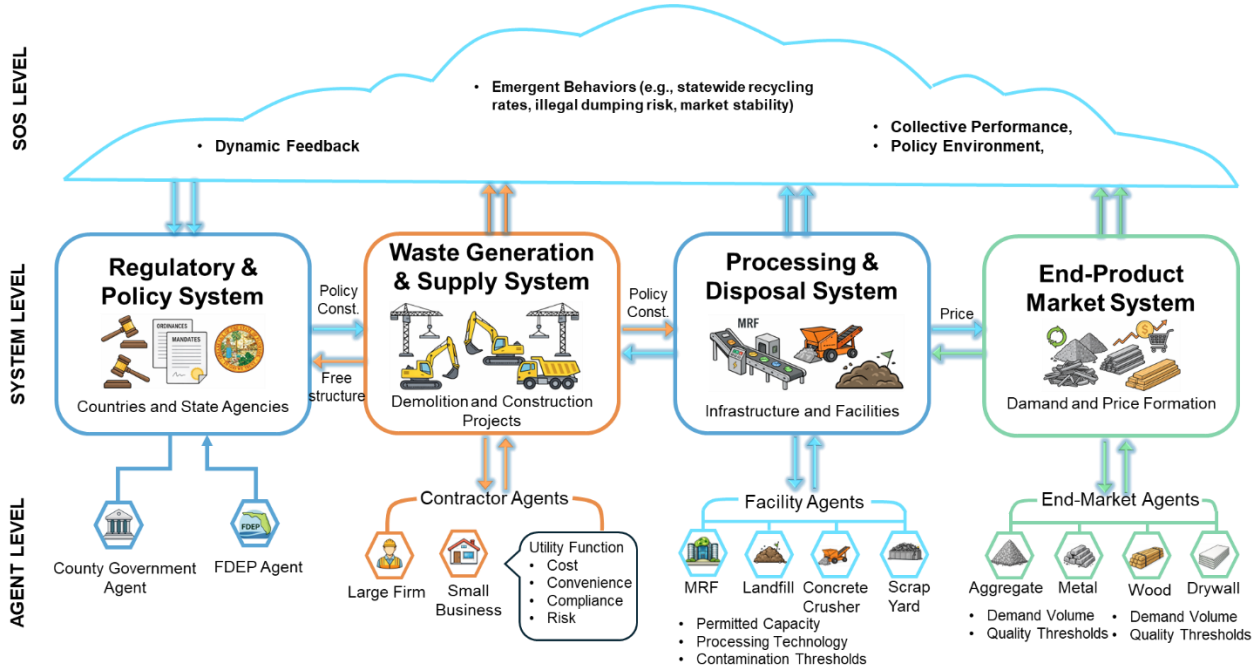

Figure 2. Conceptual model showing different parties involved in C&D recycling and their interactions

2.3.1 Contractor Agent: Material-Level Decision-Making

The most important modeling decision in this project concerns how contractor behavior is represented. In practice, a contractor does not make a single "recycle" or "landfill" choice for an entire project. A knowledgeable demolition contractor will pull out metals because scrap yards pay for them, separate concrete because in Florida source-separated concrete is not classified as solid waste and can be processed at no cost but send drywall to a landfill because few local markets exist for recycled gypsum. The simulation must capture these material-by-material decisions because that is how the real system operates and because aggregate diversion rates emerge from these granular choices.

When a project generates a waste event in the simulation, it produces a material profile which includes a set of material fractions (concrete and masonry, wood, metal, drywall, roofing, and mixed debris) with stochastic weights drawn from county-specific composition distributions. For each material fraction, the contractor agent evaluates four possible disposal pathways: (1) source-separate and send to a specialized receiver such as a concrete crusher or scrap yard, which is available only if a receiver for that material exists within the contractor's haul radius; (2) include in a mixed load delivered to a materials recovery facility (MRF), where the MRF processes the load and recovers recyclable fractions at its reported recovery rate; (3) include in a mixed load delivered to a landfill, with no recovery; or (4) illegal disposal, which carries very low direct cost but exposes the contractor to detection risk and penalties. The contractor selects the pathway that maximizes a utility score reflecting four factors identified in the literature as the primary determinants of waste management decisions: (1) cost, (2) convenience, (3) compliance, and (4) risk.

The Cost factor captures the direct financial impact of the pathway: the tipping fee or revenue received (negative cost for scrap metal), the hauling cost proportional to distance, and any on-site sorting labor required for source separation. Research consistently identifies cost as the strongest predictor of contractor waste routing decisions [33], [34]. The Convenience factor captures the time and friction associated with the pathway, including travel time to the facility, expected wait in queue, documentation requirements, and the number of separate trips required for source-separated loads. Behavioral research on C&D management consistently finds that contractors often select slightly more expensive options that are faster and simpler, what the literature terms the "hassle factor", because time on a job site is money, and administrative complexity diverts attention from production work [35]. The Compliance factor represents the value of meeting regulatory requirements. When a diversion ordinance is active, choosing a pathway that contributes to meeting the diversion target has positive compliance value because it avoids the penalty for non-compliance. When the contractor holds a deposit, choosing a pathway that produces documented diversion increases the likelihood of deposit recovery. The Risk factor captures the expected cost of adverse outcomes: for illegal disposal, this is the probability of detection multiplied by the expected fine; for sending a contaminated load to a strict facility, this is the probability of rejection multiplied by re-routing cost. Research on contractor risk perception [36] shows that contractors systematically overweight penalties relative to equivalent gains.

This utility function serves as the mechanism through which every policy intervention enters the simulation. A diversion ordinance adds compliance value for pathways that contribute to meeting the threshold and penalty risk for those that do not. A deposit-refund system adds an upfront cost to the Cost factor that is recoverable through the Compliance factor upon documented diversion. A tipping fee change directly alters the Cost factor for every material-pathway combination. A material landfill ban dramatically increases the Risk factor for landfill pathways by introducing rejection probability at the gate. This transparency (i.e., every policy maps to a specific, traceable change in contractor decision-making) is what makes the model useful for policy design. A county official can see not only whether a policy increases diversion, but why it does so and through which behavioral channel.

2.3.2 Facility Agent: Processing, Capacity, and Investment

Each materials recovery facility (MRF), landfill, transfer station, concrete crusher, and scrap yard in the simulation is represented as a facility agent with both operational and strategic behaviors. On the operational side, the facility processes incoming loads according to its technology and capacity. When a truck arrives carrying a load routed by a contractor agent, the facility inspects it depending on facility policy and staffing. If the contamination level of the load exceeds the facility's rejection threshold, the load is rejected, and the contractor must re-route to another facility, incurring additional hauling cost and time delay. Accepted loads enter the processing queue, where they are handled according to the facility's technology (crushing, screening, manual sorting, or mechanical sorting) with processing times that vary by technology type and load composition. The processing produces output streams tracked by material type: recyclable product, fuel-grade material, and residual for disposal. When more loads arrive than the facility can process within a given time window, a queue forms, increasing the effective Convenience cost that contractors experience and potentially discouraging further routing to that facility.

On the strategic side, each facility evaluates annually whether to invest in capacity expansion or technology upgrades. This investment decision is modeled as a probability that increases with sustained high utilization and revenue margin: a facility operating consistently near

capacity with positive margins is likely to invest, while one with low utilization has little incentive to do so. Real-world facility investment also depends on permitting timelines, financing availability, and market outlook, factors that the model acknowledges as simplifications and addresses through sensitivity testing of the investment responsiveness parameter. When a facility invests, it adds processing capacity, improves product quality, or both which are changes that affect the supply and quality of recycled products available to the market.

2.3.3 Regulator agent:

The regulator agent represents county government and is the primary interface through which the prototype user defines the policy scenario under test. Its parameters include the diversion ordinance threshold, covered project scope, enforcement staffing (which determines the probability that any given project will be audited for compliance), penalty schedules, deposit-refund structure, tipping fee levels at county-operated facilities, materials banned from landfill disposal, facility certification tier definitions, and procurement mandate specifications. Each of these parameters maps directly to a change in one or more terms of the contractor utility function or the facility agent's acceptance rules, as described above. Through this interface, the user configures both the regulatory environment and the market context (e.g., tipping fees, demand conditions, and active demand-side interventions) that define the complete scenario under test.

2.3.4 Market Conditions

A recurring finding in the C&D recycling literature is that supply-side policies (e.g., mandates, fee incentives, landfill bans) can fail when they are not accompanied by sufficient demand for the recycled products those policies generate [33], [34]. This is not a theoretical concern for Florida. Recycled concrete aggregate, the highest-volume recycled C&D product, must compete with abundant and inexpensive virgin aggregate from Florida's limestone quarries. FDEP has identified market development as a priority for improving C&D recycling, and facility operators consistently report that the availability of end markets is one of the binding constraints on recycling growth.

The simulation treats market conditions as user-configurable boundary conditions that reflect the county's actual situation. The market conditions under which those policies operate are an essential input, but they are best provided by the practitioner who knows the local market rather than computed by a model using uncertain assumptions.

For each material type that the simulation tracks, the user specifies three type of information on their local knowledge: (1) the current market value of the recycled product (expressed as the net revenue to the processing facility) and the price of competing virgin material, (2) whether the local market can absorb additional volume at that price or whether capacity constraints exist that would limit growth, and (3) whether a demand-side intervention (e.g., county procurement mandate or a state specification approval) is active in the scenario being tested. These parameters enter the simulation through two channels. The market value is already embedded in the facility's tipping fee schedule: a concrete crusher that can sell recycled aggregate profitably charges a low gate fee or accepts material for free; a facility that struggles to sell its output charges more to cover operating costs. The market capacity flag determines whether the simulation reports a risk warning: if a policy scenario significantly increases the volume of recycled material produced and the user has indicated that the local market has limited absorption capacity, the prototype flags potential market saturation as a risk in its output dashboard, alerting the user that the policy's projected diversion rate may not be sustainable without demand-side support.

2.3.5 Agent Interactions and System Structure

The agents in the simulation do not operate in isolation; they interact through well-defined channels of information and material flow. Understanding these interactions is essential because policy effects propagate through them. Table 1 maps every flow between agent pairs. For example, a tipping fee increase at the county landfill (Regulator → Facility) alters the Cost term in the contractor's utility function (affecting Contractor decisions), which changes the volume and composition of material arriving at MRFs (Contractor → Facility), which affects facility utilization, revenue, and product output (Facility → Market), which in turn affects recycled product prices (Market → All agents) that feed back into the next round of contractor decisions.

Table 1. Agent Interaction Map

From	To	Information / Material Exchanged	Effect on Receiving Agent
Contractor	Facility	Material loads (type, tonnage, contamination)	Determines facility throughput, queue length, revenue
Facility	Contractor	Tipping fees, acceptance/rejection decisions, weight tickets	Alters Cost and Risk terms in utility function; provides compliance documentation
Regulator	Contractor	Policy requirements: diversion threshold, penalties, deposit amounts, audit probability	Alters Compliance and Risk terms in utility function
Contractor	Regulator	Compliance reports, fee and deposit payments (or non-compliance)	Determines county revenue, compliance statistics, enforcement workload
Regulator	Facility	Certification requirements, material ban lists, inspection mandates	Modifies facility acceptance rules, investment incentives

2.4 Phase 3: Implementation and Validation

The conceptual model developed in Phase 2 is translated into a functional computational simulation using AnyLogic simulation software. The prototype is delivered with a structured input interface consisting of three panels. The County Configuration Panel allows the user to adjust local conditions such as tipping fees, facility locations (including neighboring-county facilities), the approximate number of active C&D-generating permits per year, and the current observed diversion rate for baseline calibration. The Policy Design Panel allows the user to configure policy instruments: a diversion ordinance and setting its threshold, specifying deposit amounts and refund rules, adjusting fee schedules, selecting materials for landfill bans, defining facility certification tiers, and configuring procurement mandates. The Results Dashboard displays, after each simulation run, time-series projections of the diversion rate, the probability of meeting a user-specified target, the cost per additional ton diverted relative to baseline, the distribution of contractor costs by firm size, facility utilization and queue wait times, illegal dumping incidence, county fiscal balance, and environmental metrics.

Validation Protocol

The model is validated through three sequential stages designed to ensure that the simulation's outputs are credible enough to support real policy decisions.

In the first stage, conducted at TAG Meetings 1 and 2, the conceptual model's agent logic, material flow pathways, and interaction architecture are presented to TAG members, including

county solid waste officials and demolition contractors, for face validation. TAG members evaluate whether the modeled decisions and pathways match real-world practice, and identified discrepancies are corrected before coding proceeds.

In the second stage, the model is calibrated against a single representative Florida county chosen for the availability of the diversion-rate and material-flow data needed for calibration. Calibration targets include not only the aggregate diversion rate but also, where county data are available, material-specific diversion rates and the ratio of C&D tonnage going to MRFs versus landfills. Matching multiple targets simultaneously reduces the possibility that the model reproduces the correct aggregate outcome through incorrect internal mechanisms.

In the third stage, presented at TAG Meeting 3, a systematic sensitivity analysis identifies which input parameters most strongly influence model outputs. Parameters tested include the market price metrics, facility capacity levels, enforcement probability, and investment responsiveness. This analysis serves two purposes: it reveals where the model is most sensitive to data uncertainty, guiding priorities for additional data collection, and it identifies which policy levers produce the largest changes in system-level outcomes.

2.5 Phase 4: Scenario Analysis

The validated model is used to conduct a structured scenario analysis in close collaboration with TAG members. The scenarios are organized to address the full range of policy options available to Florida counties, progressing from the status quo baseline through single-instrument policies to layered packages. Each scenario is run on a representative county and is simulated at one-year and five-year horizons with stochastic replications.

Scenario A: Status Quo Baseline: Many Florida counties operate without a comprehensive C&D diversion ordinance. Contractor routing decisions in these counties are driven by tipping fee differentials, hauling distances, and established habits. Disposal costs vary significantly across the state: in South Florida, landfill tipping fees often exceed $80–$100 per ton, whereas in many central and northern counties, fees are typically in the range of $40–$60 per ton. This variation creates differing economic incentives for recycling, with higher disposal costs generally encouraging diversion and lower costs reducing the financial attractiveness of recycling options. FDEP data show that C&D recycling rates have fluctuated in several counties in recent years despite growing construction activity, suggesting that market forces alone are not producing sustained improvement. The status quo scenario models this baseline condition with no policy interventions active, establishing the diversion rate trajectory, facility utilization, and illegal dumping incidence against which all other scenarios are measured. Without this counterfactual, it would be impossible to determine whether any observed improvement under a policy intervention is attributable to the policy or would have occurred anyway.

Scenario B: Diversion Ordinance: Lee County, Florida, has established one of the most structured construction and demolition (C&D) diversion programs in the state. The ordinance requires covered projects to meet minimum diversion targets and incorporates a fee- and compliance-based mechanism tied to building permits. While other Florida jurisdictions have implemented recycling requirements or waste management policies, few have adopted a comparably prescriptive, enforcement-oriented diversion framework. The Lee County model combines economic incentives and enforcement mechanisms, including project-based fees and penalties for non-compliance. However, there remains significant uncertainty regarding the transferability of this approach to other counties, given differences in recycling facility capacity, contractor behavior, and local governance structures. This scenario models a Lee County–inspired

ordinance design, incorporating a tiered fee structure and probabilistic enforcement (e.g., audit likelihood based on staffing capacity). Within the contractor decision framework, compliance is modeled as a utility tradeoff between the cost of diversion and the expected penalty of non-compliance. This structure allows for rational non-compliance when expected penalties are insufficient, consistent with observed contractor behavior in regulatory environments. The simulation evaluates resulting diversion rates, compliance patterns, enforcement burden, and system-level impacts, including facility capacity and illegal dumping dynamics.

Scenario C: Economic Incentive Package Without a Mandate: Many Florida counties face political constraints that make it difficult to pass a diversion ordinance. An alternative approach is to restructure economic incentives (i.e., tipping fees and deposits) to make recycling the financially rational choice without a legal mandate. This scenario explores whether economic instruments alone (i.e., differential tipping fees between landfills and recycling facilities, deposit-refund systems tied to building permits, or combinations of both) can shift contractor routing behavior sufficiently to achieve meaningful diversion improvements without a legal mandate. The underlying logic is straightforward: if the cost of landfilling exceeds the cost of recycling by a sufficient margin, contractors should rationally redirect material toward recycling facilities. In practice, however, the relationship between fee differentials and behavioral change is neither linear nor uniform. Small contractors operating on thin margins may respond differently than large firms with dedicated waste management staff, and the threshold at which a fee differential changes behavior, rather than simply increasing disposal costs, is not well established. Similarly, deposit-refund systems create a different incentive structure by shifting the financial consequence from the point of disposal to the point of permit issuance, giving contractors a direct financial stake in documenting diversion. The simulation tests these instruments both individually and in combination to answer questions that cannot be resolved through qualitative reasoning: What is the minimum fee differential required to produce measurable changes in contractor routing? Is the deposit or the fee the more effective behavioral lever, and does the answer differ by contractor firm size? When combined, do these instruments reinforce each other or produce diminishing returns by targeting the same decision channel? And at what point does escalating disposal cost begin to push contractors toward illegal dumping rather than toward recycling (i.e., a threshold that defines the practical upper limit of any fee-based strategy?)

Scenario D: Demand-Side Market Creation: Scenarios B and C focus on the supply side of the C&D recycling system (i.e., pushing more material toward recycling facilities through mandates or economic incentives.) However, increasing the supply of recycled materials is only effective if sufficient market demand exists to absorb the output. In Florida, recycled aggregate must compete with abundant and inexpensive virgin limestone, creating a persistent market disadvantage that discourages facility operators from investing in the processing capacity and product quality improvements needed to grow. This scenario examines whether demand-side interventions can break this cycle by providing the stable revenue floor that supply-side policies alone cannot deliver. Examples of such supply side policies include (1) county procurement mandates requiring a minimum percentage of recycled aggregate in public infrastructure projects, and (2) facility certification programs that link diversion credit to demonstrated quality standards [i.e., Only material delivered to certified facilities counts toward the ordinance's diversion requirement, steering loads toward higher-quality operators]. The scenario layers these demand-side mechanisms on top of the Scenario B ordinance to test a fundamental question in C&D policy design: does guaranteed demand trigger facility investment that a diversion mandate by itself does not? Beyond this central question, the simulation explores whether the combination of

procurement requirements and quality certification creates a self-reinforcing loop in which improved product quality expands market acceptance beyond the mandated procurement volume, potentially sustaining demand even if the procurement mandate were later relaxed.

Scenario E: Self-Financing Surcharge Fund: The preceding scenarios assume that recycling infrastructure (i.e., processing capacity, sorting technology, product quality) remains at its current level or improves only through private facility investment decisions. In practice, however, many facility operators identify equipment cost as a primary barrier to quality improvement, and the gap between what existing facilities can deliver and what the market demands in terms of product consistency and contamination levels constrains recycling growth regardless of what policies are in place on the supply or demand side. This scenario explores a different policy architecture: a self-financing mechanism in which a modest per-ton surcharge on C&D material delivered to landfills generates a dedicated revenue stream that is reinvested directly into recycling infrastructure improvements, such as facility equipment upgrades, digital waste tracking systems, and program administration. Unlike the other scenarios, which alter the incentive structure facing contractors or create demand for recycled products, this approach targets the capacity and quality limitations of the recycling system itself. The concept creates an inherent feedback loop: the surcharge raises the effective cost of landfilling, which shifts some material toward recycling facilities; the resulting revenue funds improvements that make those facilities more efficient and their products more marketable; better facilities attract additional material, which further reduces landfill volumes. The critical question, however, is whether this feedback loop is self-sustaining or self-defeating because as landfill volumes decline in response to the surcharge, so does the revenue the surcharge generates, potentially starving the very investments that produced the improvement. The simulation is uniquely suited to trace this dynamic over a multi-year horizon, testing whether the system stabilizes at a higher diversion rate with a reduced but sufficient revenue stream, or whether it collapses as declining landfill tonnage erodes the funding base. The scenario also examines how the allocation of surcharge revenue affects outcomes, i.e., whether directing funds primarily toward equipment upgrades, toward information infrastructure, or toward a balanced combination produces the sustained impact on system-wide diversion performance.

Scenario F: Material-Specific Landfill Bans: Scenario B tests a percentage-based diversion mandate that requires project-level compliance tracking, dedicated enforcement staff, and administrative infrastructure that some counties may be unable or unwilling to establish. This scenario examines a structurally different regulatory approach: rather than requiring contractors to demonstrate that a certain percentage of their total waste was diverted, material-specific landfill bans prohibit the disposal of designated recyclable materials at the landfill gate. The enforcement logic shifts entirely. Instead of auditing individual projects after the fact, compliance is verified at the point of disposal through load inspections at the facility. This makes material bans administratively simpler and potentially more politically feasible for counties that lack the staffing or institutional capacity for a full diversion ordinance. The scenario focuses on high-value, high-volume material streams (e.g., concrete, metal, and clean wood) that already have established processing infrastructure in most Florida counties and that collectively represent the majority of demolition debris by weight. By prohibiting these materials from entering landfills, the ban effectively forces source separation at the project site, since contractors who include banned materials in their loads face rejection at the gate and must absorb the cost and time of rerouting to an appropriate facility. The simulation addresses a set of questions that are central to evaluating whether this approach is a viable alternative to percentage-based mandates: Can bans targeting a

limited number of high-value materials achieve diversion rates comparable to those produced by a comprehensive ordinance? How does the gate inspection rate (i.e., the probability that any given load is actually checked) affect both compliance behavior and enforcement cost? Most critically, do material bans increase illegal dumping of the banned materials, as contractors facing rejection at the landfill gate seek unauthorized disposal rather than bearing the rerouting cost? This last question represents a significant concern that county officials raise when material bans are proposed, and the simulation is designed to quantify the relationship between ban stringency, inspection intensity, and illegal disposal incidence under county-specific conditions

3 Statement of Novelty

The proposed research advances the field in two distinct and complementary ways, each of which addresses a documented limitation in the existing literature and practice.

The first contribution is the development of the only simulation platform whose primary design purpose is the evaluation of C&D regulatory and policy instruments. A substantial body of simulation research exists in the C&D domain, but it has focused overwhelmingly on optimizing reverse logistics networks to minimize transportation costs and landfill use, modeling processing technologies to improve sorting efficiency and contamination removal, or quantifying waste generation rates and composition profiles for planning purposes. These models treat the policy environment (i.e., the ordinances, fee structures, deposit systems, and enforcement mechanisms that shape the decisions of every actor in the system) as a fixed background condition rather than a variable of interest. The proposed prototype inverts this relationship. Policy is the independent variable; system performance is the dependent variable. The simulation asks not "how does the C&D system work?" but rather "how does the C&D system respond when the rules change?" This reorientation fills a gap that multiple literature reviews have identified as a critical research need: the absence of tools that can predict the system-level consequences of regulatory design choices before those choices are implemented.

The second contribution is the integration of literature-grounded behavioral decision-making into a multi-method simulation framework in a way that prior C&D models have not achieved. Most existing models assume that contractors are cost-minimizing rational actors who will automatically select the cheapest disposal option available to them. Empirical research tells a different story. Studies grounded in the Theory of Planned Behavior, evolutionary game theory, and prospect theory consistently demonstrate that contractor decisions are shaped by habit, risk aversion, information availability, perceived administrative hassle, firm-size effects, and peer behavior; factors that pure cost optimization does not capture. The proposed prototype incorporates these findings through a utility function with coefficients drawn from published behavioral research and calibrated through practitioner validation. The model allows contractors to make material-level decisions that vary within a single project, to rationally choose non-compliance when the expected penalty is less than the compliance cost, and to resort to illegal dumping when legal disposal costs exceed their risk-adjusted willingness to pay for legitimate options. These features produce predictions that are more realistic than those of cost-minimization models. Examples include predicting unintended consequences such as increased illegal dumping, facility bottlenecks, or market saturation, outcomes that policymakers need to anticipate before implementation.

4 Practical, Specific Benefits for End Users

The project produces direct, actionable benefits for four categories of stakeholders in Florida's C&D waste management system.

County Solid Waste Directors, and Planners: The prototype's most immediate practical value lies in its ability to reduce the uncertainty that currently prevents counties from acting on C&D recycling policy. When a county solid waste director recommends a diversion ordinance to the county commission, the commissioners will ask predictable questions: Will it work here, or only in counties like Lee? Will our MRFs be able to handle the additional material? Will contractors comply, or will they just pay the fee or worse, dump illegally? How much will it cost the county to administer? Will it hurt small contractors disproportionately? The simulation provides quantified, county-specific answers to these questions before any policy is enacted.

For example, the prototype enables a county to test whether a given diversion threshold is achievable given the county's actual facility capacity, contractor base, and hauling geography, and to identify the threshold at which processing bottlenecks emerge. It provides fiscal impact projections showing the revenue from diversion fees, deposits, or surcharges alongside the administrative cost of enforcement, producing the net fiscal effect that budget offices require. It reports the probability of meeting the diversion target, not merely the projected average rate, so that officials understand the downside risk. It calculates the cost per additional ton diverted for each policy option, enabling direct cost-effectiveness comparison. And it reports contractor cost impacts by firm size, revealing whether a policy disproportionately burdens small businesses, a dimension of particular concern to county commissioners sensitive to local economic impacts.

The prototype also produces the environmental benefit quantification that elected officials increasingly need to justify policy action to the public: tons diverted from landfill, and estimated greenhouse gas emissions avoided. These metrics translate recycling rates into terms that resonate in public discourse and can be included directly in commission presentations, public comment responses, and grant applications.

FDEP and State Policymakers: At the state level, the platform addresses a longstanding question: whether Florida should develop a statewide model C&D diversion ordinance and, if so, how it should be structured. Once extended beyond the single-county prototype in a follow-on phase, the simulation could run the same ordinance design across pre-configured county templates representing urban and rural environments, high and low construction activity, and infrastructure-rich and infrastructure-poor settings to identify which elements of a model ordinance should be standardized statewide and which should be left to local discretion. This analysis provides the evidence base that FDEP would need to develop guidance for counties.

The platform can also evaluate the impact of state-level interventions that operate outside the county ordinance framework: FDOT specification approval for recycled C&D aggregate in state road construction (which would expand demand and reduce the quality-uncertainty discount that limits end-market acceptance), state grant programs targeted at MRF equipment upgrades (which would improve product quality and facility throughput), and potential statewide material-specific disposal restrictions.

Demolition Contractors and Industry Associations: The scenario analysis generates information that is directly valuable to the contractor community, particularly when proposed ordinances are under public review. For each policy scenario, the simulation quantifies the compliance cost impact by firm size category, revealing policies where compliance is cheaper than non-compliance (incentive-aligned policies that contractors should support). This cost analysis provides the quantitative evidence that industry associations need for informed participation in

public comment processes. The simulation can also identify the specific project types, material streams, and geographic circumstances under which a proposed policy creates the greatest compliance difficulty, informing industry recommendations for appropriate exemption thresholds, phase-in schedules, and small-contractor accommodations.

C&D Recycling Facility Operators: Facility operators make investment decisions (e.g., expanding capacity, purchasing new sorting or crushing equipment, seeking certification) based on expectations about future inbound material volumes, composition, and contamination levels. The simulation projects how each policy scenario changes these variables, providing the forward-looking information that operators need for investment planning. The facility certification analysis within Scenario D identifies which quality and performance standards would provide the greatest competitive advantage under different policy configurations, helping operators prioritize their improvement investments.

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