

# Validation of a Multi-Agent Simulation Engine for Urban Solid Waste Collection in Resource-Constrained Contexts

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## Abstract

Urban solid waste management in resource-constrained cities is characterized by structural constraints that limit the direct experimentation of collection strategies. In this context, simulation constitutes a relevant methodological tool, provided that the simulation engine employed is validated as a scientific instrument. This article presents the design and methodological validation of a multi-agent simulation engine, named SimWasteKin, dedicated to the analysis of urban solid waste collection systems within an abstract and controlled framework. The engine is based on a modular architecture integrating a spatio-temporal environment, agents representing collection points and collection vehicles, and a decision-making module that is distinct from output instrumentation. Validation relies on explicit criteria of structural consistency, reproducibility through random seed control, and qualitative sensitivity to key parameters. The results indicate that the engine generates coherent, stable, and interpretable dynamics under controlled initial conditions.

## Keywords

Multi-Agent Simulation, Solid Waste Collection, Decision Support, Resource-Constrained Contexts

## 1. Introduction

Urban solid waste management constitutes a structural challenge for many cities facing resource constraints, characterized by rapid population growth, poorly

planned urbanization, and limited institutional capacities [1]-[3]. In such contexts, collection systems are often subject to severe operational constraints, combining inadequate infrastructure, limited financial resources, and restricted access to reliable data. These constraints directly affect service continuity and translate into documented public health and environmental impacts [4] [5].

In response to these challenges, simulation has progressively emerged as a central methodological tool for the analysis of complex urban systems. By explicitly representing dynamic interactions among actors, resources, and constraints, simulation models provide a controlled experimental framework to explore alternative configurations and analyze systemic mechanisms that are difficult to observe in situ. In the field of solid waste management, such approaches have been used to study route planning, resource allocation, and trade-offs between operational efficiency, costs, and environmental impacts [6] [7].

However, a critical review of the literature reveals a recurrent methodological limitation. Many studies directly exploit simulation outputs to compare strategies or formulate recommendations, without subjecting the simulation engine itself to explicit and independent validation. In resource-constrained contexts, where modeling assumptions play a decisive role due to the lack of comprehensive empirical data, the credibility of results depends closely on the internal consistency, reproducibility, and interpretability of the simulation tool employed [8]-[11].

In parallel, recent research has highlighted the importance of grounding decision-making models in empirically observed practices within low-resource urban contexts. In particular, a Contextual Prioritization Index (CPI) has been proposed, derived from field-based analysis of decision criteria mobilized by waste management actors in Kinshasa [12]. This index formalizes the interaction between sanitary, logistical, social, and institutional factors within a structured decision-support framework adapted to constrained environments.

However, while such an approach provides a strong empirical basis for decision-making, it does not allow for controlled experimentation or systematic evaluation of its effects on system performance. In this respect, simulation becomes a necessary complementary tool, enabling the testing of decision rules within a controlled and reproducible environment.

The validation of a simulation engine does not necessarily aim to establish its predictive accuracy with respect to a specific real-world situation. In methodological research, it rather consists in demonstrating that the engine constitutes a reliable experimental instrument, capable of producing coherent and differentiated behaviors under controlled initial conditions. This approach is widely recognized in modeling and simulation, where model validity relies on the transparency of assumptions, the stability of simulated dynamics, and the traceability of implemented mechanisms [13] [14].

It is within this perspective that the present article is situated. It proposes the design and methodological validation of a multi-agent simulation engine dedicated to the study of urban solid waste collection systems in resource-constrained contexts. The article focuses exclusively on validating the engine as a scientific

tool, relying on criteria of structural consistency, reproducibility, and qualitative sensitivity.

The use of the engine outputs for the substantive comparison of waste collection strategies is deliberately not addressed here and will be examined in separate studies. By explicitly dissociating tool validation from the analysis of the results it can generate, this article seeks to contribute to good practices in urban systems modeling and to provide a robust methodological framework for subsequent comparative analyses.

## 2. Methods

### 2.1. General Framework and Simulation Engine

The simulation engine developed in this study, referred to as SimWasteKin, is designed according to an experimental posture explicitly oriented toward the methodological validation of a simulation tool, rather than toward the production of predictive results. Simulation is mobilized as a scientific instrument intended to analyze the coherence and robustness of decision-making mechanisms under controlled conditions, in line with established practices in the modeling and simulation of complex systems [9] [13]. Accordingly, the validity of the engine is assessed based on internal criteria, including structural consistency, stability of simulated dynamics, and reproducibility of outputs, independently of any fine-grained empirical calibration.

A central principle guiding the design of the engine is experimental comparability. All internal configurations strictly share the same spatial, temporal, and demographic initial conditions, ensuring that any differences observed in the model outputs can be attributed solely to the activated decision rules. The adopted validation strategy combines structural validation, explicit control of stochastic components, and qualitative sensitivity analysis with respect to key parameters. This approach is intended to ensure that the engine constitutes a coherent, reproducible, and interpretable experimental tool, suitable for subsequent comparative analyses that are distinct from the results presented in this paper.

### 2.2. Overall Architecture of the Simulation Engine

The proposed architecture is based on a modular multi-agent organization, structured to explicitly dissociate the simulation environment, agent dynamics, decision-making logic, and output instrumentation. As illustrated in **Figure 1**, all agents evolve within a shared spatial environment, which serves as a common invariant reference for all internal configurations of the engine.

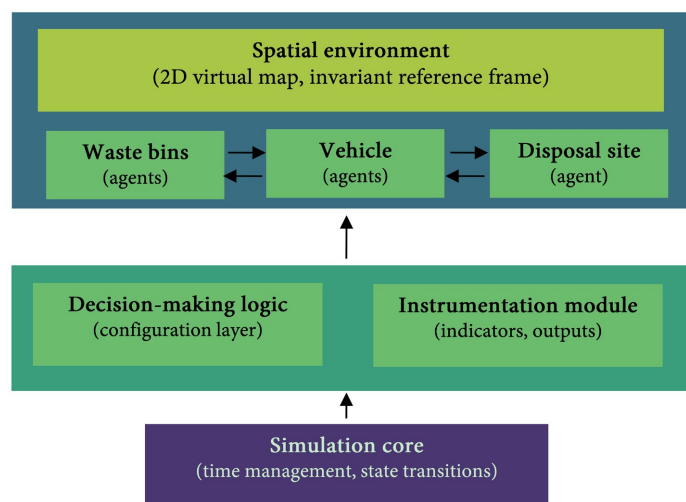
Three categories of entities interact within this environment. Collection points, modeled as waste bins, represent continuous waste generation processes and capacity-related saturation phenomena. Mobile collection agents, modeled as collection vehicles, perform movement, collection, and unloading operations according to explicit rules. A single treatment point, modeled as a disposal site, receives the collected waste flows. Temporal coordination and synchronization of interac-

tions are ensured by a central simulation core, which manages time progression and state transitions.

Decision-making logic is encapsulated within a dedicated module, allowing contrasting internal configurations to be activated without modifying either the environment or the agent structure. An independent instrumentation module collects simulation outputs and computes predefined indicators, without exerting any feedback on system dynamics. This functional separation ensures that observed behaviors can be attributed to the simulated rules rather than to implicit coupling effects, which is a necessary condition for the methodological evaluation of the proposed device.

Within this framework, three distinct decision systems are considered, corresponding to different operational paradigms. The first configuration (S1) represents a traditional scheduled collection system, in which vehicles follow predefined routes and fixed schedules without real-time information on bin fill levels. A constant collection efficiency is applied to reflect the fact that bins are not fully emptied. The second configuration (S2) corresponds to a reactive IoT-based system, in which collection is triggered when bin fill levels exceed a predefined threshold, based on sensor data that may be subject to stochastic failures. The third configuration (S3) represents a context-aware intelligent system, in which collection decisions rely on the prioritization of high-risk zones, based on a prioritization index.

All configurations operate under identical spatial, temporal, and parametric conditions, ensuring that any observed differences in outputs are exclusively attributable to the implemented decision rules.



**Figure 1.** Conceptual architecture of the simulation engine.

### 2.3. Spatial and Temporal Framework

The spatial framework of the engine is represented by a two-dimensional virtual map, used as a metric support for distance and movement calculations, without reference to any real geographical area. This map is generated during engine initialization and remains invariant throughout the simulation. Collection points are

distributed across distinct functional zones, with explicit constraints imposed on inter-point distances within the same zone in order to prevent geometric overlap and to preserve a regular spatial structure.

The temporal dynamics are conceptually defined in continuous time, allowing for the progressive integration of waste generation, agent movements, and collection operations. The total simulation duration is expressed in simulated days, enabling temporal acceleration without altering the underlying calculation rules. This spatio-temporal framework provides a coherent basis for analyzing system dynamics independently of any specific geographical or temporal configuration.

In practice, the continuous-time dynamics are numerically approximated using a discrete-time simulation scheme with a one-minute time step. At each iteration, waste generation, agent movements, and state transitions are updated sequentially.

The simulation engine is implemented in a web-based environment using an asynchronous execution architecture, allowing the system to handle large-scale simulations while maintaining computational efficiency. Continuous processes are approximated through incremental updates at each time step, ensuring consistency between the conceptual formulation and the practical implementation.

#### 2.4. Agent Modeling and Internal Dynamics

The internal dynamics of the simulated system rely on the joint formalization of continuous waste generation processes and discrete collection and transport processes. Waste generation is modeled as a continuous flow that depends on the number of users associated with each collection point. For a collection point  $i$ , associated with  $U_i$  users and a daily per-user waste generation rate  $r$ , the hourly waste generation rate is defined by Equation (1):

$$p_i = \frac{r \cdot U_i}{24} \quad (1)$$

This formulation allows waste accumulation to be represented as a gradual process, independently of the simulation time step.

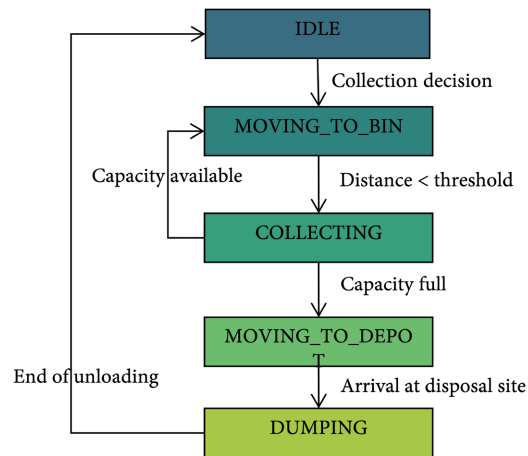
The evolution of the amount of waste stored at a collection point is then described by a continuous accumulation relationship. Let  $W_i(t)$  denote the quantity of waste present at time  $t$ , at collection point  $i$ . Equation (2) expresses the increase in this quantity over a time interval  $\Delta t$ , as long as no collection operation is performed:

$$W_i(t + \Delta t) = W_i(t) + p_i \cdot \Delta t \quad (2)$$

Each collection point is characterized by a nominal capacity  $C_i$ . When the accumulated quantity exceeds this capacity, an overflow is generated. This overflow at collection point  $i$  and time  $t$ , is defined by Equation (3) as the excess amount of waste relative to the nominal capacity:

$$O_i(t) = \max(0, W_i(t) - C_i) \quad (3)$$

Collection and transport operations are performed by mobile agents whose behavior is formalized using a finite state machine, as illustrated in **Figure 2**. This state machine structures the sequences of inactivity, movement, collection, and unloading, with transitions governed by explicit distance thresholds and capacity constraints. Unloading cycles are treated as non-interruptible in order to preserve the logistical consistency of operational sequences. Taken together, this modeling framework enables a coherent articulation of continuous waste generation processes and discrete collection operations within a controlled simulation setting.



**Figure 2.** State machine for a collection vehicle agent.

## 2.5. Global Parameters of the Simulation Engine

The operation of the simulation framework relies on a set of global parameters defined prior to each execution and kept constant throughout a run. These parameters delimit the demographic, operational, and spatio-temporal dimensions of the simulated system, as well as the nominal capacities of the involved entities. They notably include the number of collection points and vehicles, their associated capacities, bounds on waste generation, the simulation duration, and temporal acceleration factors.

The selection and calibration of these parameters are based on a combination of literature-informed assumptions and empirical observations from low-resource urban contexts. In particular, parameters related to waste generation, operational constraints, and decision conditions draw on field-based evidence of stakeholder practices and system dynamics observed in cities characterized by limited infrastructure, data scarcity, and constrained institutional capacities [12], ensuring a realistic yet controlled simulation setting.

All global parameters are applied identically across the internal configurations considered, thereby neutralizing any exogenous variation related to parameter settings. Stochastic components are controlled through an explicit random seed to ensure the repeatability of executions. The selected parameter values and their associated ranges are summarized in **Table 1**, which serves as the parametric reference for the methodological validation of the simulation framework.

**Table 1.** Global parameters of the simulation engine.

Parameter	Description	Value/Range	Unit
Number of collection points	Total number of waste bins simulated in the environment	$\geq 20$	-
Bin capacity	Maximum capacity before overflow	$\geq 30$	kg
Number of users per bin	Number of users associated with a collection point	2 - 15	-
Waste generation per user	Amount of waste generated per user per day	0.5	kg/day
Number of vehicles	Number of mobile collection agents	$\geq 2$	-
Vehicle capacity	Maximum transport capacity of a collection vehicle	$\geq 1500$	kg
Zonal assignment	Functional zone assigned to each vehicle	Fixed	-
Inter-bin distance	Metric distance between bins within the same zone	0.5 - 2.0	km
Reference temporal unit	Scientific time step used for calculations	1	hour
Simulation duration	Total temporal horizon of a simulation run	$\leq 365$	days
Temporal acceleration factor	Simulation speed multiplier	1 - 1000	-
Weather conditions	Simplified state influencing	dry/rainy	-
Traffic period	Time interval influencing mobility	day/night	-
Random seed	Value controlling stochastic	specified	-

In addition to the parameter ranges presented in **Table 1**, an explicit baseline configuration is defined to ensure reproducibility and clarity of the validation experiments. This configuration provides a controlled reference framework and does not aim to represent a calibrated real-world case.

The detailed baseline parameter values used in the validation runs are summarized in **Table 2**.

**Table 2.** Baseline parameter configuration used in validation experiments.

Parameter	Value	Unit
Number of collection points	10,000	-
Number of vehicles	5	-
Vehicle capacity	3000	kg
Agents per vehicle	4	-
Simulation duration	90	days
Waste generation per user	0.5	kg/day
Service time window	02:00-23:00	h
Labor cost	4	USD/day/agent
Fuel cost	1.5	USD/L
Truck maintenance cost	1500	USD
Maintenance interval	2500	km
Nuisance cost	0.15	USD/kg

All validation experiments are conducted under this baseline configuration unless explicitly stated otherwise.

## 2.6. Instrumented Indicators

The instrumentation of the simulation framework relies on a set of indicators defined a priori and automatically computed during simulation runs. These indicators are used as observation variables intended to characterize the overall behavior of the simulated system, without intervening in agent dynamics. Their definition aims to provide an analytical support for assessing the coherence, stability, and interpretability of the outputs within the scope of methodological validation.

The indicators cover several complementary dimensions, including operational, economic, environmental, and health-related aspects, in order to capture different levels of system functioning. In the context of this article, they are not employed to establish performance comparisons between internal configurations, but rather to examine how outputs evolve under controlled initial conditions and well-defined parametric variations. The list of instrumented indicators and their definitions is summarized in **Table 3**, which serves as the observational reference used during the validation of the simulation framework.

**Table 3.** Instrumented indicators implemented in the simulation engine.

Dimension	Indicator	Description	Unit
Operational	Total distance traveled	Cumulative distance traveled by all collection vehicles	Km
Operational	Amount of waste collected	Total mass of waste effectively collected	Kg
Operational	Amount of waste generated	Total mass of waste generated by collection points	Kg
Operational	Total collection time	Cumulative time devoted to collection and transport operations	hours
Economic	Fuel consumption	Estimated fuel consumption associated with vehicle movements	liters
Economic	Maintenance cost	Cost associated with vehicle maintenance	US dollars
Economic	Labor cost	Aggregated cost of collection crews	US dollars
Environmental	Transport-related emissions	Estimated emissions associated with vehicle movements	kg CO <sub>2</sub>
Environmental	Overflowed waste quantity	Cumulative mass of overflowed waste	Kg
Environmental	Nuisance index	Relative index based on waste overflow and zone density	-

The main derived indicators are computed using explicit formulations to ensure transparency and reproducibility.

Waste generation at the bin level is modeled as a continuous accumulation process and is computed at each time step as:

$$GR_i(t) = U_i \times \frac{W}{24 \times 60} \times \Delta t \times M_{rain} \times M_{holiday} \quad (4)$$

where  $GR_i(t)$  is the waste generation rate at bin  $i$  at time  $t$ ,  $U_i$  is the number of users associated with the bin  $i$ ,  $W$  is the daily waste generation per user (kg/day),  $\Delta t$  is the time step (minutes), and  $M_{rain}$ ,  $M_{holiday}$  are multiplicative factors representing weather and seasonal effects.

The total distance traveled by vehicles is computed from spatial coordinates and converted into kilometers. Fuel consumption is estimated as:

$$F = \alpha \cdot D \quad (5)$$

where  $F$  is the fuel consumption (liters),  $D$  is the traveled distance (km), and  $\alpha = 0.5$  L/km is the fuel consumption coefficient.

Transport-related emissions are computed as:

$$E_{CO_2} = \beta \cdot F \quad (6)$$

where  $E_{CO_2}$  denotes CO<sub>2</sub> emissions (kg) and  $\beta = 2.6$  kg/L is the emission factor.

The global cost is defined as:

$$C_{global} = C_{capex} + C_{opex} + C_{san} \quad (7)$$

where  $C_{capex}$  is the capital expenditure,  $C_{opex}$  is the operational cost, and  $C_{san}$  is the sanitary cost.

The sanitary cost is modeled as a cumulative function of overflow over time:

$$C_{san} = \sum_{t=0}^T \left( \sum_{i=1}^N \max(0, W_i(t) - C_i) \right) \cdot r \cdot \Delta t \quad (8)$$

where  $W_i(t)$  is the waste level at bin  $i$  at time  $t$ ,  $C_i$  is the capacity of bin  $i$ ,  $r$  is the nuisance cost rate (USD/kg/min), and  $N$  is the number of bins.

These formulations ensure that all indicators are explicitly defined, traceable to model assumptions, and reproducible under identical simulation conditions.

## 2.7. Methodological Validation Criteria

The methodological validation of the simulation framework is based on a set of criteria explicitly defined prior to any execution. These criteria are intended to assess the ability of the framework to operate as a reliable scientific simulation instrument, independently of any substantive interpretation of the internal configurations. They are applied systematically under controlled initial conditions and constitute the analytical basis for the results presented in Section 3.

The selected criteria cover the core dimensions of simulation model validity, including structural consistency, reproducibility, stability of dynamics, and interpretability of the generated behaviors. Their purpose is to identify potential logical inconsistencies, numerical instabilities, or uncontrolled responses to parametric variations. The full set of validation criteria, together with their evaluation modalities, is summarized in **Table 4**, which formalizes the methodological reference framework used to assess the robustness of the simulation engine.

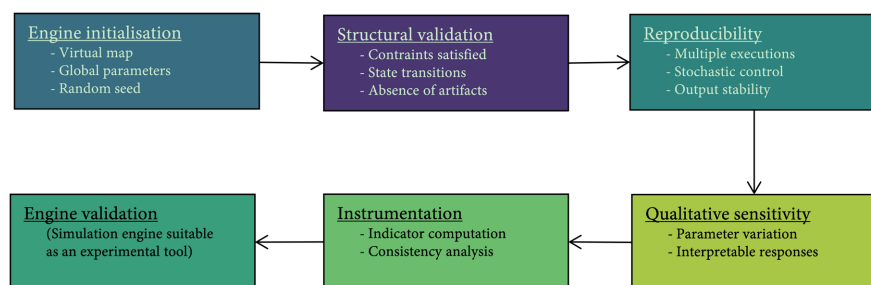
**Table 4.** Methodological validation criteria of the simulation engine.

Criterion	Definition	Evaluation method	Purpose
Structural consistency	Conformity of the engine with defined rules and constraints	Verification of state transitions, capacities, and operational rules	Prevent invalid states and numerical artifacts
Behavioral consistency	Plausibility of agent action sequences	Qualitative analysis of simulated sequences	Ensure interpretable dynamics
Reproducibility	Invariance of outputs under identical initial conditions	Explicit control of the random seed and repeated executions	Ensure experimental repeatability
Temporal stability	Absence of unjustified drifts or instabilities	Observation of indicators over extended time horizons	Verify engine robustness
Qualitative sensitivity	Progressive response to parametric variations	Controlled parameter variation tests	Assess coherence of model responses
Controlled differentiation	Ability to produce distinct behaviors according to activated rules	Qualitative comparison of outputs across configurations	Verify engine expressiveness
Traceability	Ability to link outputs to implemented rules	Analysis of internal states and decision rules	Strengthen scientific interpretability

## 2.8. Validation Workflow

The validation of the simulation framework is conducted according to an explicit procedural sequence, summarized in **Figure 3**. This workflow formalizes how the different validation steps are articulated during a simulation run, from the initial configuration to the analysis of instrumented outputs.

The process begins with the configuration of the experimental framework, including global parameter settings and, where applicable, the specification of the random seed. It then proceeds with the controlled execution of the engine, during which the operational rules and internal dynamics are activated without external intervention. The generated outputs are subsequently collected and structured in accordance with the defined instrumentation scheme, before being examined against the established validation criteria. This sequential organization ensures that each execution follows an identical protocol, thereby guaranteeing result traceability and the reproducibility of the validation process.

**Figure 3.** Validation workflow of the SimWasteKin simulation engine.

To support the validation process, a series of repeated simulation runs is performed for each decision configuration (S1, S2, S3), with a total of 30 independent runs per configuration.

The global parameters remain fixed across runs, including the number of bins, number of vehicles, capacities, simulation duration, and environmental conditions. Stochastic variability is introduced through the random distribution of users across bins.

Stability is evaluated based on the consistency of key output indicators across runs, including total cost, distance traveled, and overflow levels. A configuration is considered stable if variations remain within a limited range and if the relative ranking between configurations is preserved.

### 3. Results

#### 3.1. Structural Validation

Structural validation assesses the conformity of the simulation engine with the formal constraints defined during its design. Capacity rules for both collection points and vehicles are systematically respected, and overflow mechanisms are triggered exclusively when the predefined thresholds are reached. State transitions of mobile agents occur solely according to the specified finite state machine, with no unauthorized transitions or incoherent cycles. Operational sequences of collection, transport, and unloading comply with the prescribed ordering constraints and non-interruptibility requirements defined for critical operations. No situation corresponding to an invalid system state (e.g., collection without spatial contact, unhandled capacity exceedance, undefined state transition) is generated by the engine under the tested conditions.

#### 3.2. Reproducibility

Reproducibility is evaluated through explicit control of the stochastic components integrated into the model. Under identical global parameters, simulation runs produce consistent and structurally stable outputs, both in terms of agent trajectories and aggregated indicators computed by the instrumentation module. This property ensures that simulated dynamics are governed by the initial conditions and the defined operational rules.

When the stochastic realization is modified while keeping an identical parametric framework, the observed variations remain consistent with the intended stochastic mechanisms and do not affect the structure of the dynamics or the validity of operational sequences. This behavior confirms that randomness is properly controlled and that the framework satisfies the requirements of experimental repeatability expected of a scientific simulation engine.

To support these observations, representative numerical values from repeated simulation runs are considered. Across the 30 runs performed, the results show strong consistency in terms of order of magnitude within each configuration. For instance, the total cost for the S1 system remains on the order of  $3.5 \times 10^5$ , with

limited variation across runs.

### 3.3. Stability and Qualitative Sensitivity

Engine stability is examined over extended temporal horizons and under controlled parametric variations. Instrumented indicators evolve continuously when key parameters (such as capacities, waste generation rates, or decision thresholds) are modified within their predefined ranges. No unjustified discontinuities or erratic behaviors are introduced by these variations. The engine responses to parameter changes remain interpretable in light of the implemented rules, and the overall system dynamics preserve their structural coherence.

This controlled qualitative sensitivity indicates that the engine is sufficiently expressive to reflect configuration changes while remaining stable, a necessary condition for its subsequent use in distinct comparative analyses.

The results also show that the relative behavior of the configurations remains consistent across runs. In particular, the S2 system systematically produces higher total costs (on the order of  $1.0 \times 10^6$ ), while S3 stabilizes around  $7.5 \times 10^5$ , and S1 remains lower but with higher sanitary costs. This ranking is preserved across all runs, confirming the robustness of the simulation engine under stochastic variability.

## 4. Discussion

The presented validation results confirm the methodological relevance of the proposed simulation framework as a scientific instrument for the analysis of complex urban systems [15]. The adopted structure, based on an explicit separation between environment, agents, decision-making logic, and instrumentation, satisfies the requirements of internal consistency, reproducibility, and interpretability commonly associated with research-oriented simulation engines. This principle of modularity, widely recognized in the literature, facilitates the identification of mechanisms underlying simulated dynamics and limits implicit coupling effects that could bias analysis [16] [17].

From a scientific positioning perspective, this work aligns with established methodological frameworks in modeling and simulation, which emphasize the need to clearly distinguish tool validation from the exploitation of the results it produces. The validation criteria mobilized (structural validation, explicit control of stochasticity, and qualitative sensitivity analysis) are consistent with recommendations from foundational work on simulation model verification and validation [9]. By explicitly focusing on evaluating the simulation framework rather than comparing strategies, the article adopts a methodological posture that remains underdeveloped in applied studies of urban solid waste management, where simulation is often directly used for optimization or decision-making purposes.

The use of an abstract spatio-temporal framework constitutes a structuring methodological choice. This abstraction enables a focus on the fundamental mechanisms of the simulated system while reducing dependence on context-spe-

cific data, which are often incomplete or heterogeneous in resource-constrained urban environments. The simulation literature highlights that such a level of abstraction enhances interpretability and conceptual transferability of models, at the cost of an acknowledged limitation in local descriptive capacity [18]-[20]. This trade-off between generality and realism is consistent with the validation objectives pursued and clearly delineates the scope of applicability of the proposed framework.

This study presents several limitations that should be acknowledged. The simulation environment is based on an abstract spatial representation, without direct integration of real-world geographic data. The model considers a single disposal site and simplified representations of weather and traffic conditions, which may limit the realism of certain operational dynamics.

In addition, the model is not calibrated using empirical data, as the objective of this study is to validate the internal consistency and methodological robustness of the simulation engine rather than to reproduce specific real-world scenarios.

These limitations imply that the results should be interpreted as illustrative of system behavior under controlled conditions. Future work will focus on integrating real geographic data, refining environmental dynamics, and performing empirical calibration to enhance external validity.

## 5. Conclusions

This article has presented the design and methodological validation of a multi-agent simulation engine, named SimWasteKin, dedicated to the analysis of urban solid waste collection systems in resource-constrained contexts. By adopting an experimental posture explicitly oriented toward tool validation, the study has examined the internal consistency, reproducibility, and stability of the engine, independently of any substantive exploitation of the simulated internal configurations.

The validation results demonstrate that the adopted architecture (based on a clear separation between environment, agents, decision-making logic, and instrumentation) meets the criteria expected of a scientific simulation engine. The implementation of structural validation procedures, stochastic control, and qualitative sensitivity analysis confirms that the engine generates coherent and interpretable dynamics under controlled initial conditions. These properties constitute an essential prerequisite for any subsequent simulation-based comparative analysis.

The primary contribution of this work is methodological. It lies in the formalization of a validated, transparent, and reproducible simulation framework designed to support comparative studies of waste collection strategies in urban environments subject to strong resource constraints. The abstraction choices made, while limiting any direct operational interpretation of the outputs, clarify the engine's scope of applicability and enhance the readability of the simulated mechanisms.

Future work will focus on the controlled exploitation of SimWasteKin in in-depth comparative analyses of waste collection strategies, as well as on the pro-

gressive integration of empirical data to examine the sensitivity of the engine to specific urban contexts. By explicitly dissociating tool validation from the analysis of the results it produces, this article contributes to good practices in urban systems modeling and simulation and provides a solid methodological foundation for further research.

## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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